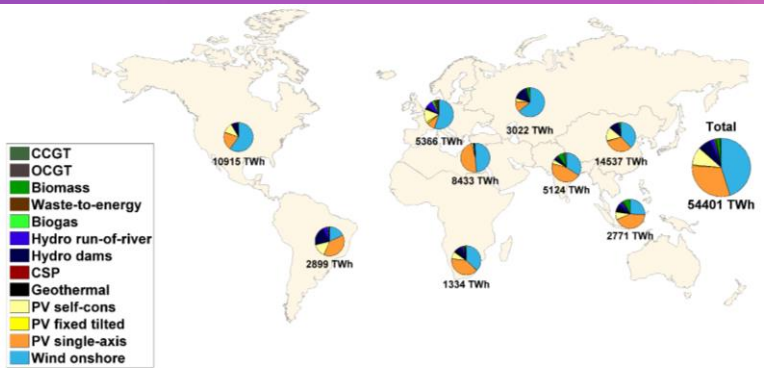

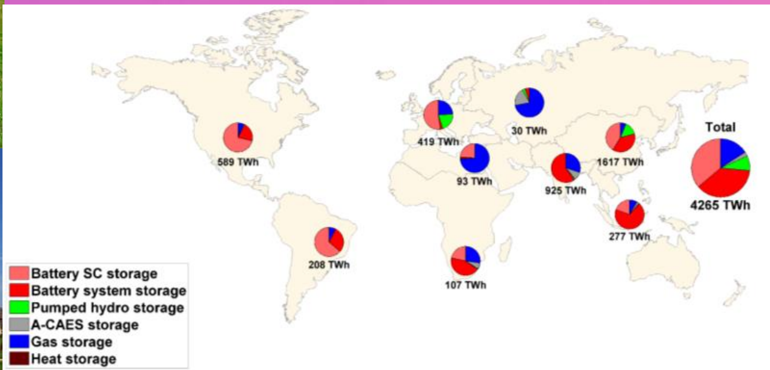

PV IN 100% RE SCENARIOS

NEO CARBON ENERGY

Christian Breyer
Lappeenranta University of Technology, Finland
ISES Webinar on PV Market Development
webinar, December 8, 2016

COP21 Agreement in Paris

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United Nations FCCC/CP/2015/L.9

Framework Convention on Climate Change

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Conference of the Parties
Twenty-first session
Paris, 30 November to 11 December 2015

Agenda item 4(b)
Durban Platform for Enhanced Action (decision 1/CP.17)
Adoption of a protocol, another legal instrument, or an agreed outcome with legal force under the Convention applicable to all Parties

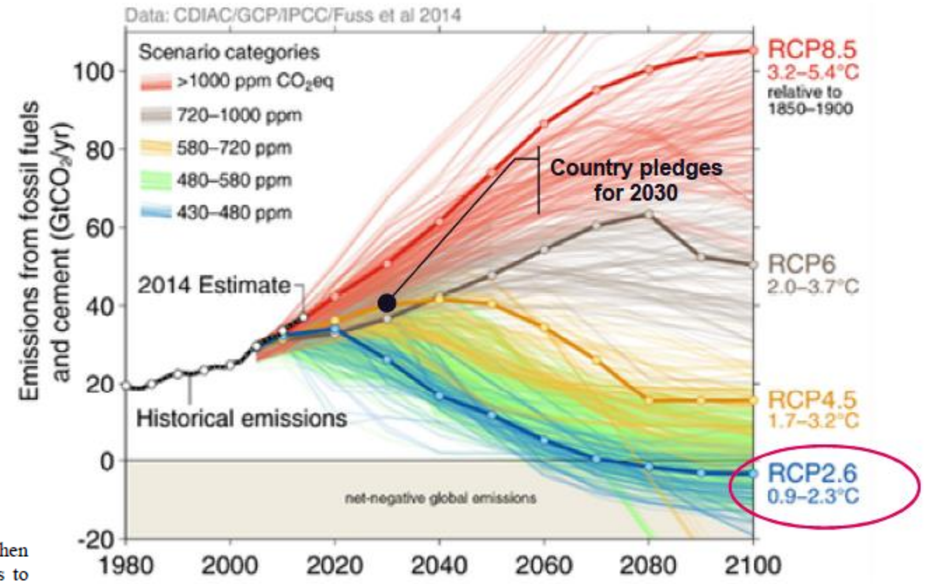
ADOPTION OF THE PARIS AGREEMENT

Article 2

1. This Agreement, in enhancing the implementation of the Convention, including its objective, aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty, including by:
   (a) Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
   (b) Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production;
   (c) Making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Article 4

1. In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.



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Global Energy Transition Scenarios

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Global Energy Transition Scenarios

		PV capacity				share PV on TPED-elec			share solar total on TPED-all			
		2030	2040	2050	2100	2030	2040	2050	2030	2040	2050	2100
	[Ref]	[GWp]	[GWp]	[GWp]	[GWp]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
BNEF	[7]	1799	3687			7,7 %	14,3 %					
Greenpeace - ER	[18]	2839	4988	6745		11,4 %	16,5 %	19,9 %	6,1 %	14,1 %	22,2 %	
Greenpeace - Adv ER	[18]	3725	6678	9295		13,7 %	18,2 %	20,2 %	7,7 %	18,4 %	29,1 %	
IEA - NPS	[9]	728	1066			2,9 %	3,9 %		0,6 %	0,9 %		
IEA - 450	[9]	938	1519			4,4 %	6,6 %		0,9 %	1,8 %		
IEA-PVPS	[19]	1570	3930	11010	133000				0,7 %	1,4 %	3,3 %	25,3 %
IRENA REmap - mix	[20]	1760				15,9 %		16,7 %	17,0 %		22,0 %	
IRENA REmap - doubling	[20]	2520						21,7 %			29,0 %	
WWF	[21]					7,6 %	16,3 %	29,0 %	7,1 %	17,8 %	30,6 %	
IIASA-GEA - Efficiency	[22]								6,9 %		23,7 %	
IIASA-GEA - Mix	[22]								7,7 %		20,6 %	
IIASA-GEA - Supply	[22]								9,0 %		17,0 %	
IPCC - 5th AR WGIII - MESSAGE	[23]								6,4 %	12,9 %	15,3 %	42,8 %
IPCC - 5th AR WGIII - REMIND	[23]								0,4 %	2,3 %	6,6 %	40,3 %
IPCC - 5th AR WGIII - GCAM	[23]								0,4 %	1,1 %	1,3 %	2,7 %
WBGU	[24]								4,0 %	10,6 %	27,7 %	66,9 %
Jacobson and Delucchi	[25]	32700	32700	32700	32700						40,0 %	40,0 %
Shell - Mountains	[26]								1,5 %	2,4 %	3,6 %	37,7 %
Shell - Oceans	[26]	1800		20000					3,2 %	8,2 %	13,6 %	
min		730	1070	6750	32700	2,9 %	3,9 %	19,9 %	0,4 %	0,9 %	1,3 %	2,7 %
max		3730	6680	32700	133000	15,9 %	18,2 %	29,0 %	9,0 %	18,4 %	40,0 %	66,9 %
average		1960	3640	15950	82850	9,1 %	12,6 %	21,5 %	7,0 %	7,7 %	17,7 %	36,5 %

source: Breyer Ch., Bogdanov D., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24

Global Energy Transition Scenarios

		PV capacity				share PV on TPED-elec			share solar total on TPED-all			
		2030	2040	2050	2100	2030	2040	2050	2030	2040	2050	2100
	[Ref]	[GWp]	[GWp]	[GWp]	[GWp]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
BNEF	[7]	1799	3687			7,7 %	14,3 %					
Greenpeace - ER	[18]	2839	4988	6745		11,4 %	16,5 %	19,9 %	6,1 %	14,1 %	22,2 %	
Greenpeace - Adv ER	[18]	3725	6678	9295		13,7 %	18,2 %	20,2 %	7,7 %	18,4 %	29,1 %	
IEA - NPS	[9]	728	1066			2,9 %	3,9 %		0,6 %	0,9 %		
IEA - 450	[9]	938	1519			4,4 %	6,6 %		0,9 %	1,8 %		
IEA-PVPS	[19]	1570	3930	11010	133000				0,7 %	1,4 %	3,3 %	25,3 %
IRENA REmap - mix	[20]	1760				15,9 %		16,7 %	17,0 %		22,0 %	
IRENA REmap - doubling	[20]	2520						21,7 %			29,0 %	
WWF	[21]					7,6 %	16,3 %	29,0 %	7,1 %	17,8 %	30,6 %	
IIASA-GEA - Efficiency	[22]								6,9 %		23,7 %	
IIASA-GEA - Mix	[22]								7,7 %		20,6 %	
IIASA-GEA - Supply	[22]								9,0 %		17,0 %	
IPCC - 5th AR WGIII - MESSAGE	[23]								6,4 %	12,9 %	15,3 %	42,8 %
IPCC - 5th AR WGIII - REMIND	[23]								0,4 %	2,3 %	6,6 %	40,3 %
IPCC - 5th AR WGIII - GCAM	[23]								0,4 %	1,1 %	1,3 %	2,7 %
WBGU	[24]								4,0 %	10,6 %	27,7 %	66,9 %
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Shell - Mountains	[26]								1,5 %	2,4 %	3,6 %	37,7 %
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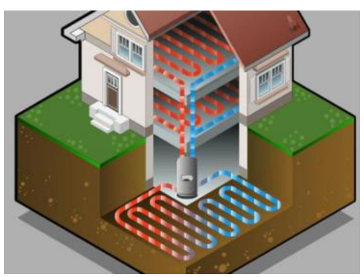
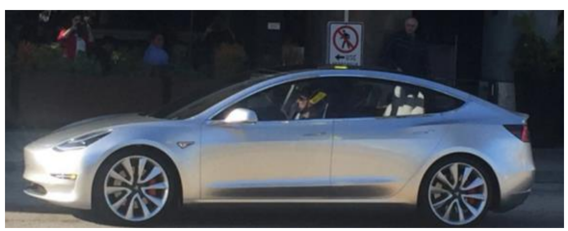
min		730	1070	6750	32700	2,9 %	3,9 %	19,9 %	0,4 %	0,9 %	1,3 %	2,7 %
max		3730	6680	32700	133000	15,9 %	18,2 %	29,0 %	9,0 %	18,4 %	40,0 %	66,9 %
average		1960	3640	15950	82850	9,1 %	12,6 %	21,5 %	7,0 %	7,7 %	17,7 %	36,5 %

Key insights:

- No consensus on capacities to be expected
  - 2030: 730 – 1960 – 3730 GW
  - 2040: 1070 – 3640 – 6680 GW
  - 2050: 6750 – 15950 – 32700 GW
- PV share on the electricity supply
  - 2030: 3% – 9% – 16%
  - 2040: 4% – 13% – 18%
  - 2050: 20% – 23% – 29%
- Solar energy share on total primary energy demand
  - 2030: 0.4% – 4% – 9%
  - 2040: 0.9% – 8% – 18%
  - 2050: 1.3% – 18% – 40%
  - 2100: 3% – 37% – 67%





Perth Seawater Desalination Plant
Potabilisation System and Drinking Water Storage Tank

Key Objective

Definition of an optimally structured energy system based on 100% RE supply

- optimal set of technologies, best adapted to the availability of the regions' resources,
- optimal mix of capacities for all technologies and every sub-region of Eurasia,
- optimal operation modes for every element of the energy system,
- least cost energy supply for the given constraints.

LUT Energy model, key features

- linear optimization model
- hourly resolution
- multi-node approach
- flexibility and expandability
- world split into 145 sub-regions

Input data

- historical weather data for: solar irradiation, wind speed and hydro precipitation
- available sustainable resources for biomass and geothermal energy
- synthesized power load data
- gas and water desalination demand
- efficiency/ yield characteristics of RE plants
- efficiency of energy conversion processes
- capex, opex, lifetime for all energy resources
- min and max capacity limits for all RE resources
- nodes and interconnections configuration

Methodology

Full system

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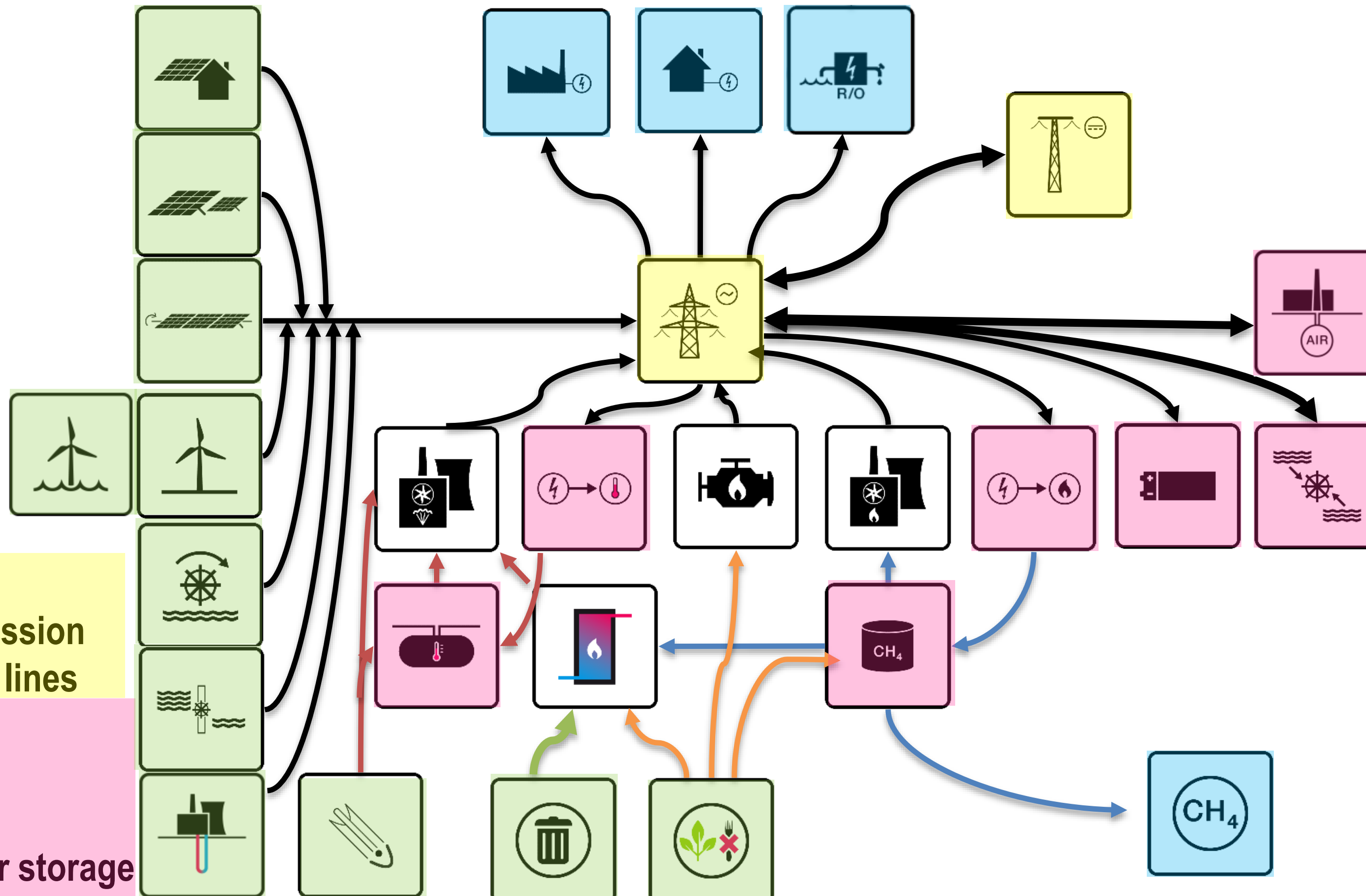
Renewable energy sources
- PV rooftop
- PV ground-mounted
- PV single-axis tracking
- Wind onshore/ offshore
- Hydro run-of-river
- Hydro dam
- Geothermal energy
- CSP
- Waste-to-energy
- Biogas
- Biomass

Electricity transmission
- node-internal AC transmission
- interconnected by HVDC lines

Storage options
- Batteries
- Pumped hydro storage
- Adiabatic compressed air storage
- Thermal energy storage, Power-to-Heat
- Gas storage based on Power-to-Gas
  - Water electrolysis
  - Methanation
  - CO_2 from air
  - Gas storage



Energy Demand
- Electricity
- Water Desalination
- Industrial Gas

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Overview on World's Regions

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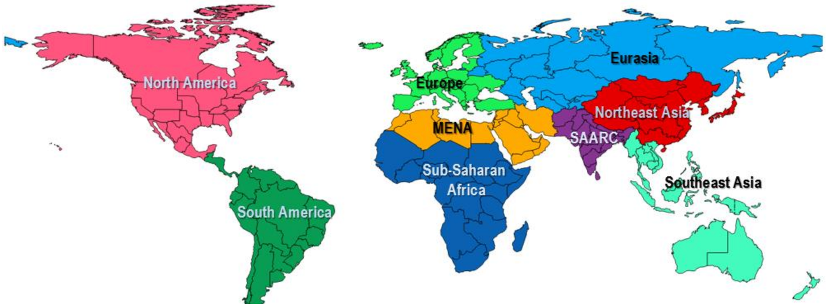
Regions	LCOE region-wide [€/MWh]	LCOE area-wide [€/MWh]	Integration benefit ** [%]	storages* [%]	grids regions' trade* [%]	Curtailment [%]	PV prosumers* [%]	PV system * [%]	Wind * [%]	Biomass * [%]	Hydro* [%]
Northeast Asia	63	56	6.0%	7%	10%	5%	16.4%	35.4%	40.9%	2.9%	11.6%
Southeast Asia	67	64	9.5%	8%	3%	3%	7.2%	36.8%	22.0%	22.9%	7.6%
India/ SAARC	72	67	5.9%	22%	23%	3%	6.2%	43.5%	32.1%	10.9%	5.4%
Eurasia	63	53	23.2%	<1%	13%	3%	3.8%	9.9%	58.1%	13.0%	15.4%
Europe	57	51	8.7%	6%	17%	2%	12.3%	14.9%	55.0%	6.6%	9.3%
MENA	61	55	10.8%	<1%	10%	5%	1.8%	46.4%	48.4%	1.3%	1.1%
Sub-Saharan Africa	58	55	16.2%	4%	8%	4%	16.2%	34.1%	31.1%	7.8%	8.2%
North America	63	53	10.1%	1%	24%	4%	11.0%	19.8%	58.4%	3.7%	6.8%
South America	62	55	7.8%	5%	12%	5%	12.1%	28.0%	10.8%	28.0%	21.1%

* Integrated scenario, supply share
** annualised costs

Key insights:

- 100% RE is highly competitive
- least cost for high match of seasonal supply and demand
- PV share typically around 40% (range 15-51%)
- hydro and biomass limited the more sectors are integrated
- flexibility options limit storage to 10% and it will further decrease with heat and mobility sector integration
- most generation locally within sub-regions (grids 3-24%)



sources: see www.researchgate.net/profile/Christian_Breyer

Cost comparison of 'cleantech' solutions

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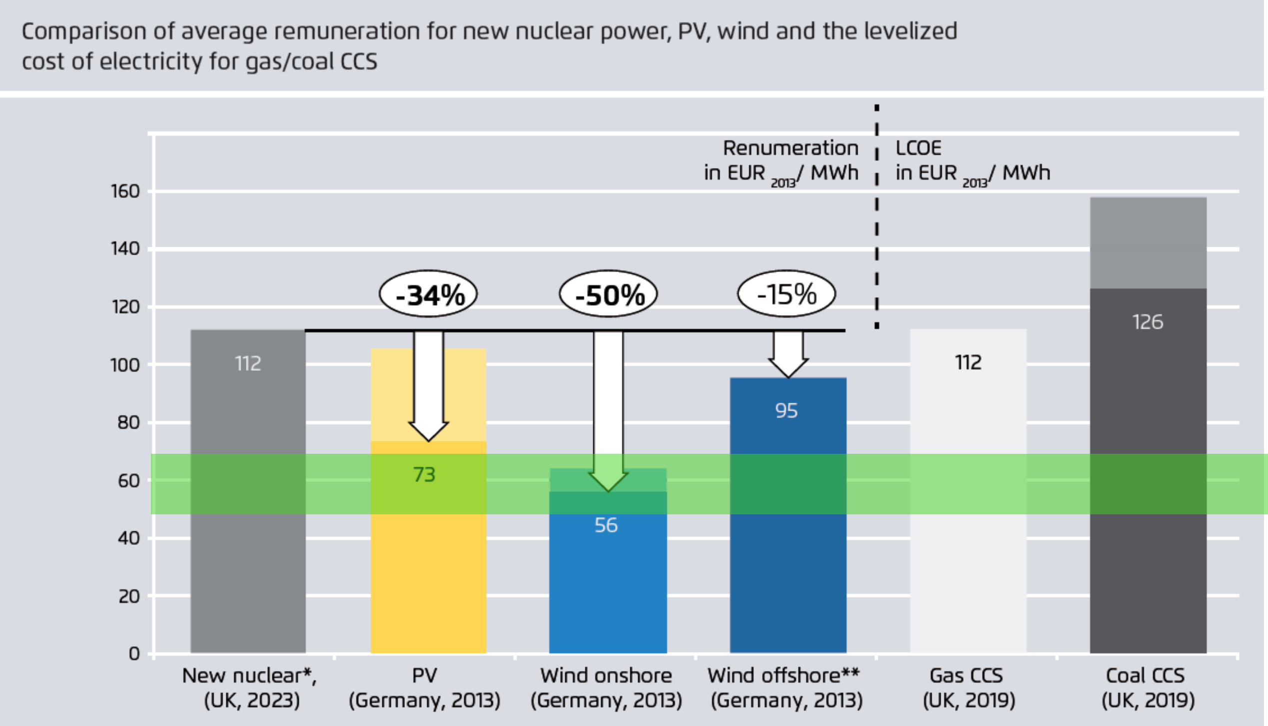

Preliminary NCE results clearly indicate 100% RE systems cost about 50-70 €/MWh for 2030 cost assumptions on comparable basis

source: Breyer Ch., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24

Key insights:

- PV-Wind-Gas is the least cost option
- nuclear and coal-CCS is too expensive
- nuclear and coal-CCS are high risk technologies
- 100% RE systems are highly cost competitive

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source: Agora Energiewende, 2014. Comparing the Cost of Low-Carbon Technologies: What is the Cheapest option; Grubler A., 2010. The costs of the French nuclear scale-up: A case of negative learning by doing, Energy Policy, 38, 5174

Results: Global view

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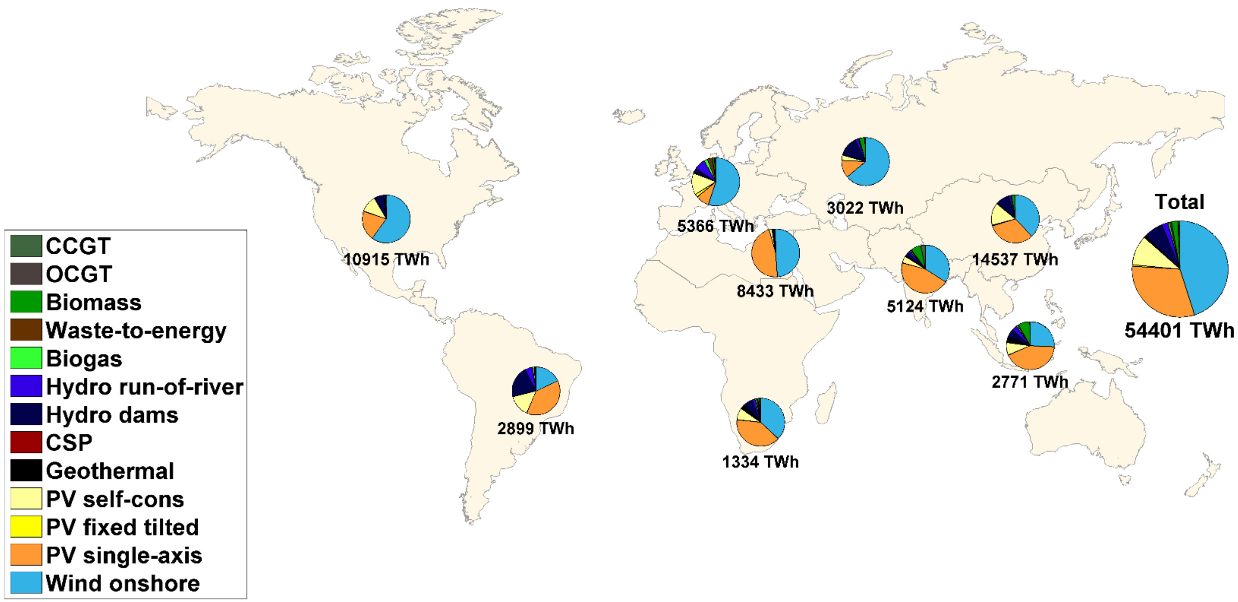
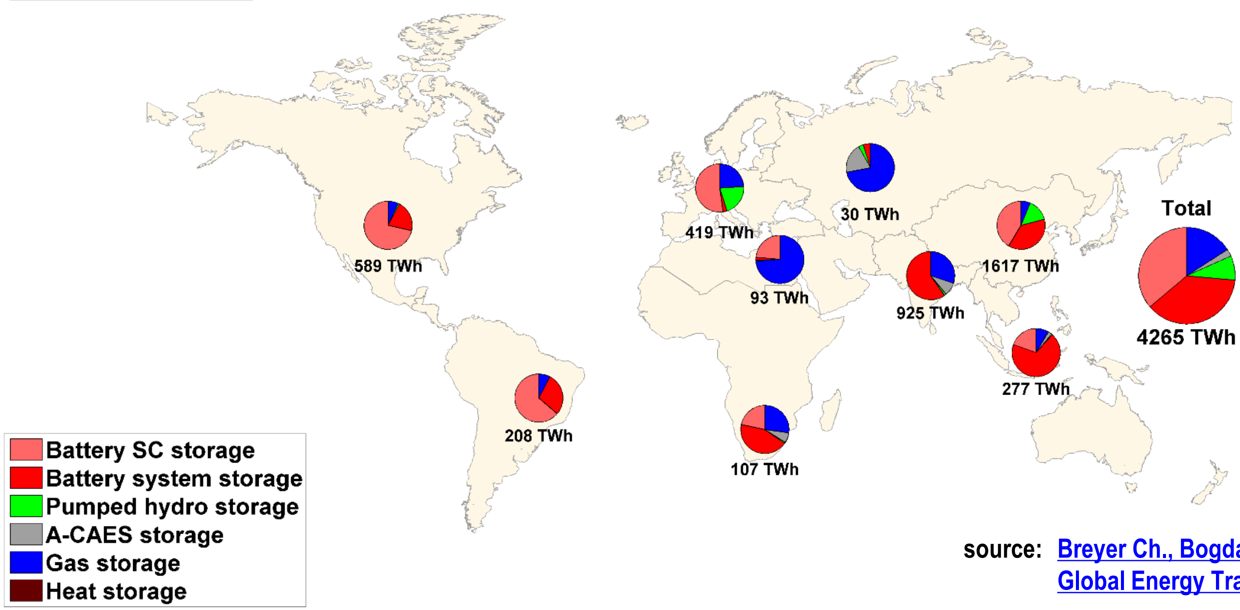


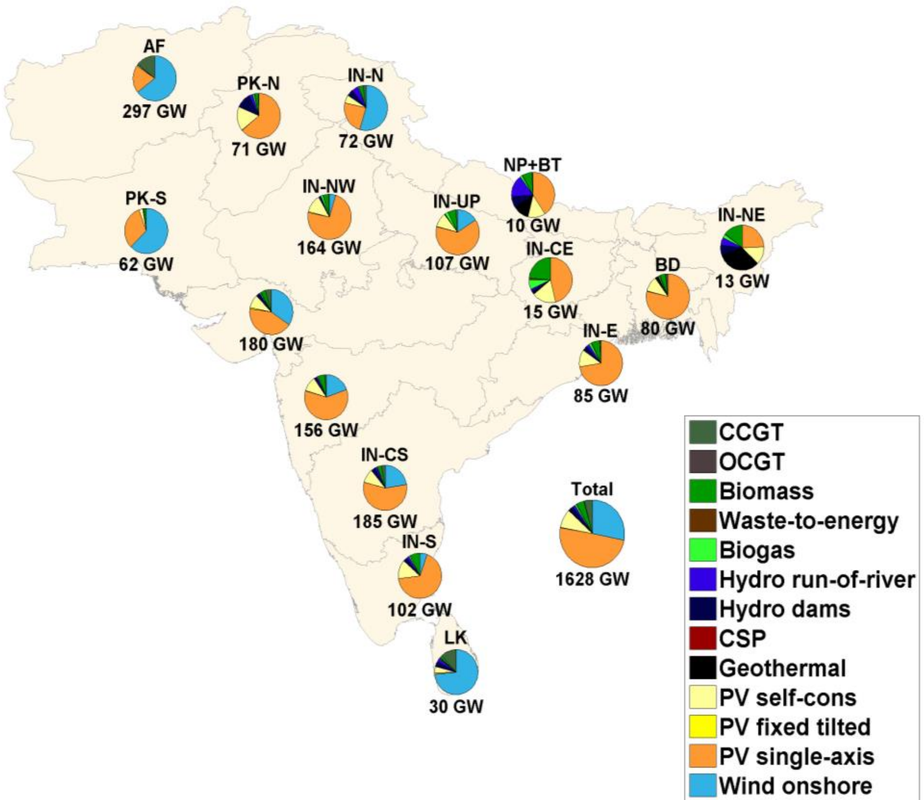


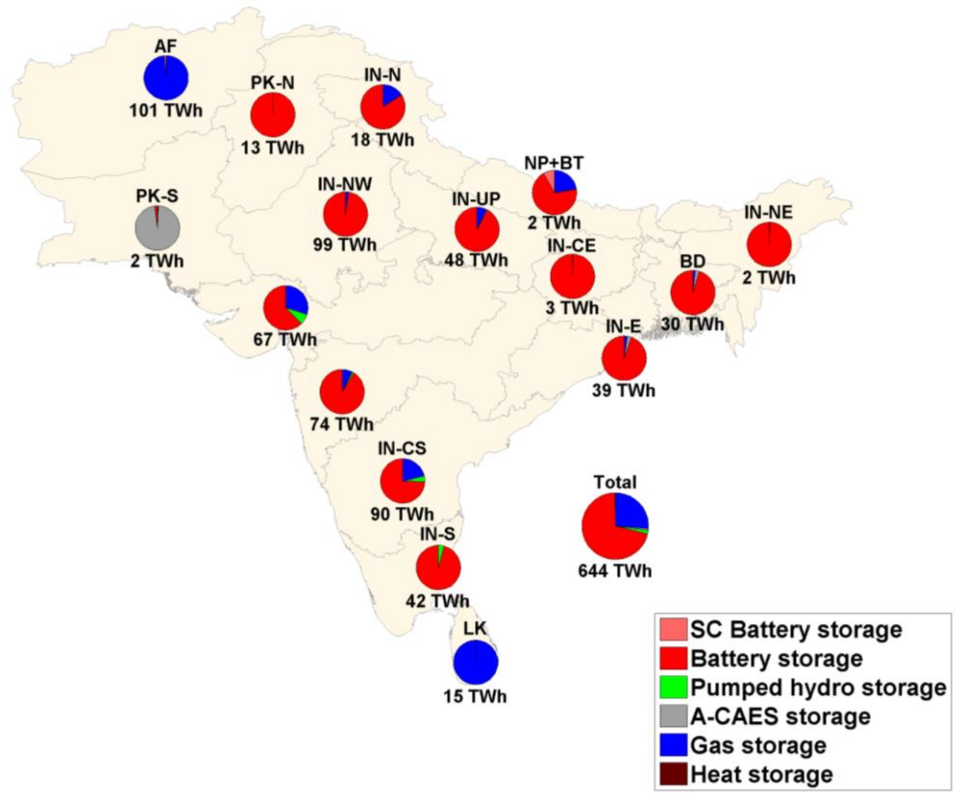
Key insights:

- population of 7948 mil
- electricity demand of 30289 / 49408 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 9086 GW 52% (region), 7142 GW 36% (area), 10998 GW 41% (integrated)
- storage of 19% / 14% / 10% of final electricity demand, thereof battery share of 63% / 69% / 75% for region / area / integrated
- trading among sub-regios of 15% / 14% for area / integrated

source: Breyer Ch., Bogdanov D., et al., 2016. On the Role of Solar Photovoltaics in Global Energy Transition Scenarios, 32nd EU PVSEC, Munich, June 20-24

Results: India/ SAARC





Key insights:

- population of 1922 mil, electricity demand of 2597 / 3376 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 947 GW 62% (region), 789 GW 54% (area), 960 GW 50% (integrated)
- storage of 24% / 21% / 19% of final electricity demand, thereof battery share of 73% / 85% / 71% for region / area / integrated
- trading among sub-regios of 14% / 23% for area / integrated

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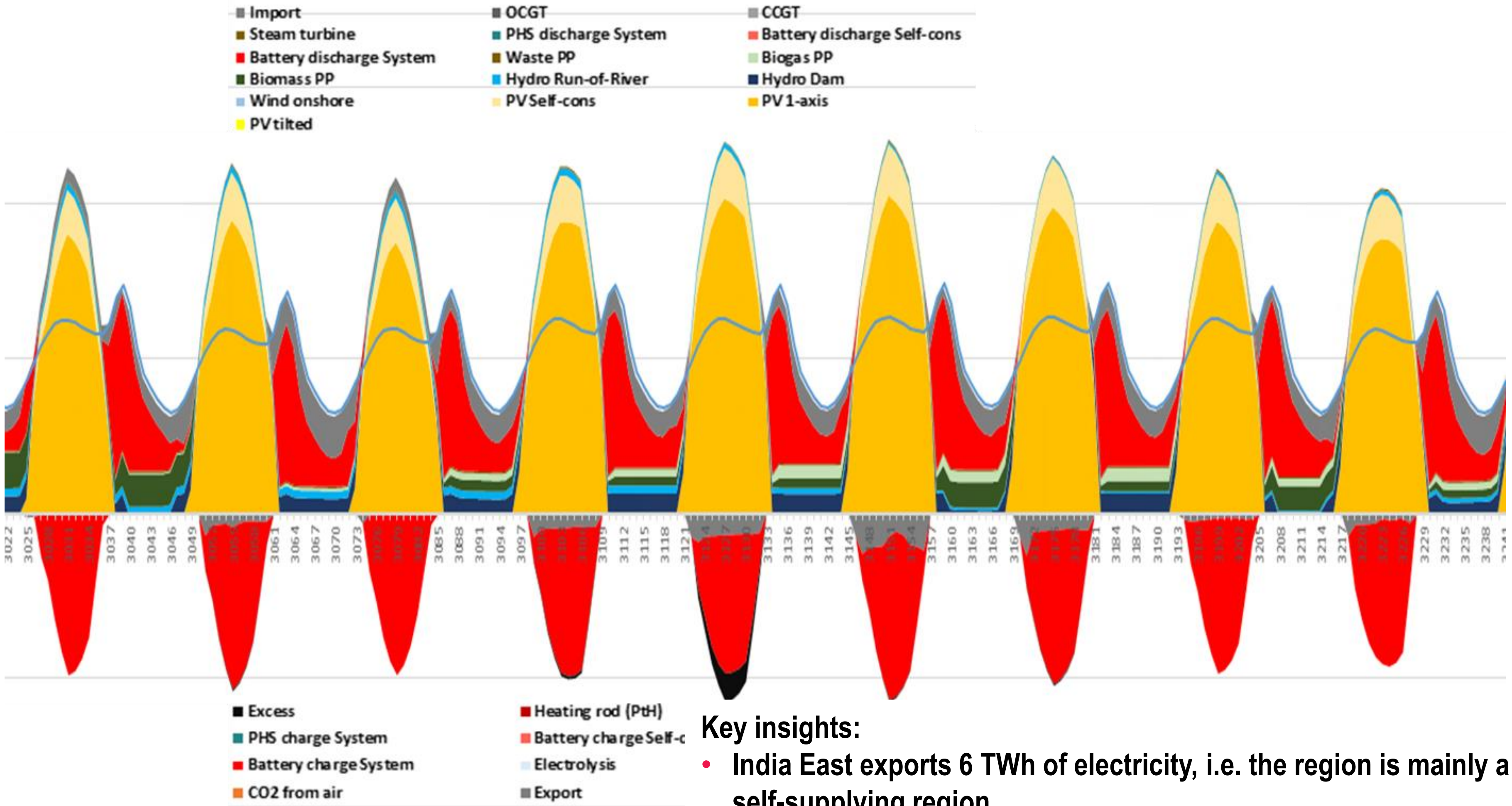
source: Gulagi A., et al., 2016. Solar Photovoltaics – A driving force towards a 100% renewable energy system for India and the SAARC region, 32nd EU PVSEC, Munich, June 20-24

Results

Net exporter region – India East



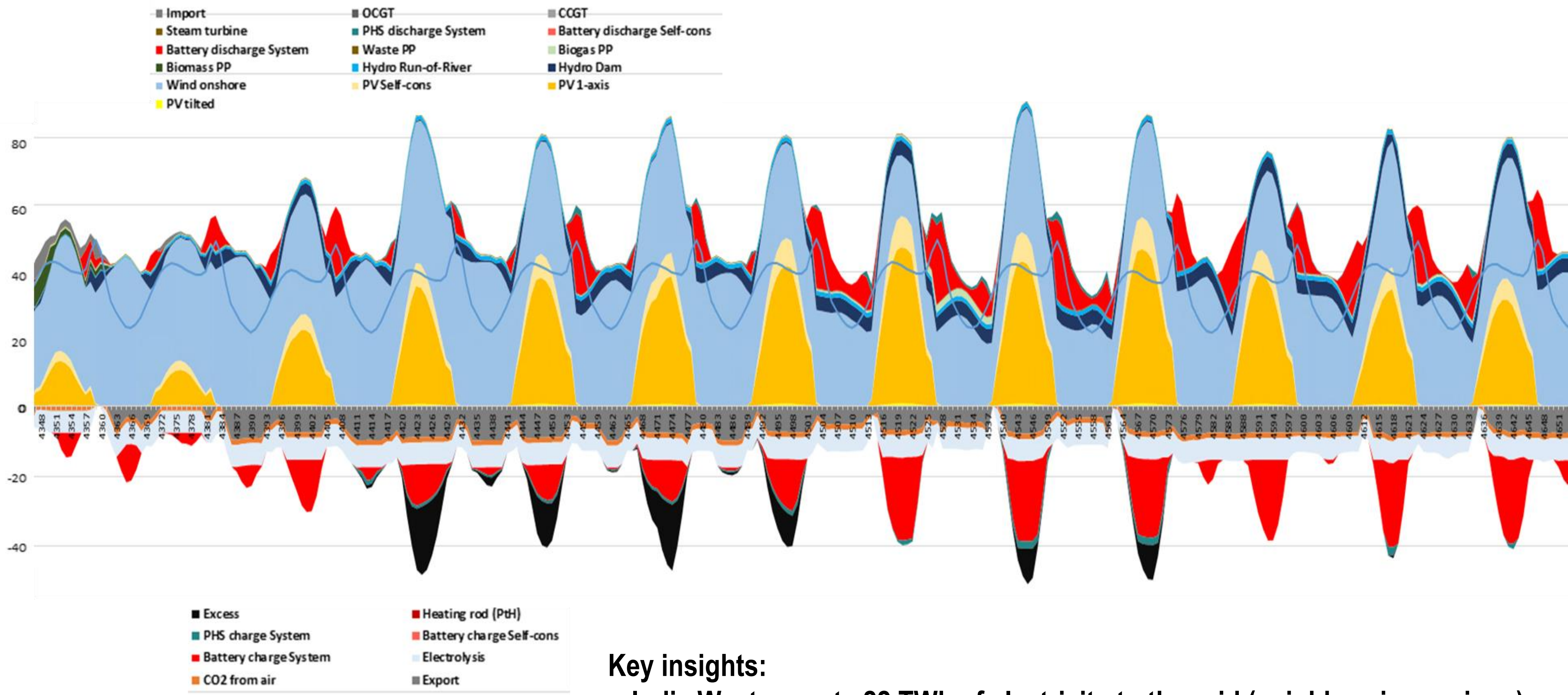
Key insights:

- India East exports 6 TWh of electricity, i.e. the region is mainly a self-supplying region
- Energy mix is mainly based on PV plus some hydro dams and biomass
- Batteries shift PV based electricity in the afternoon and night
- Flexible biomass and hydro is used in evening and night hours

source: [Gulagi A., et al., 2016. Solar Photovoltaics – A driving force towards a 100% renewable energy system for India and the SAARC region, 32nd EU PVSEC, Munich, June 20-24]

Results

Net exporter region – India West (monsoon month)



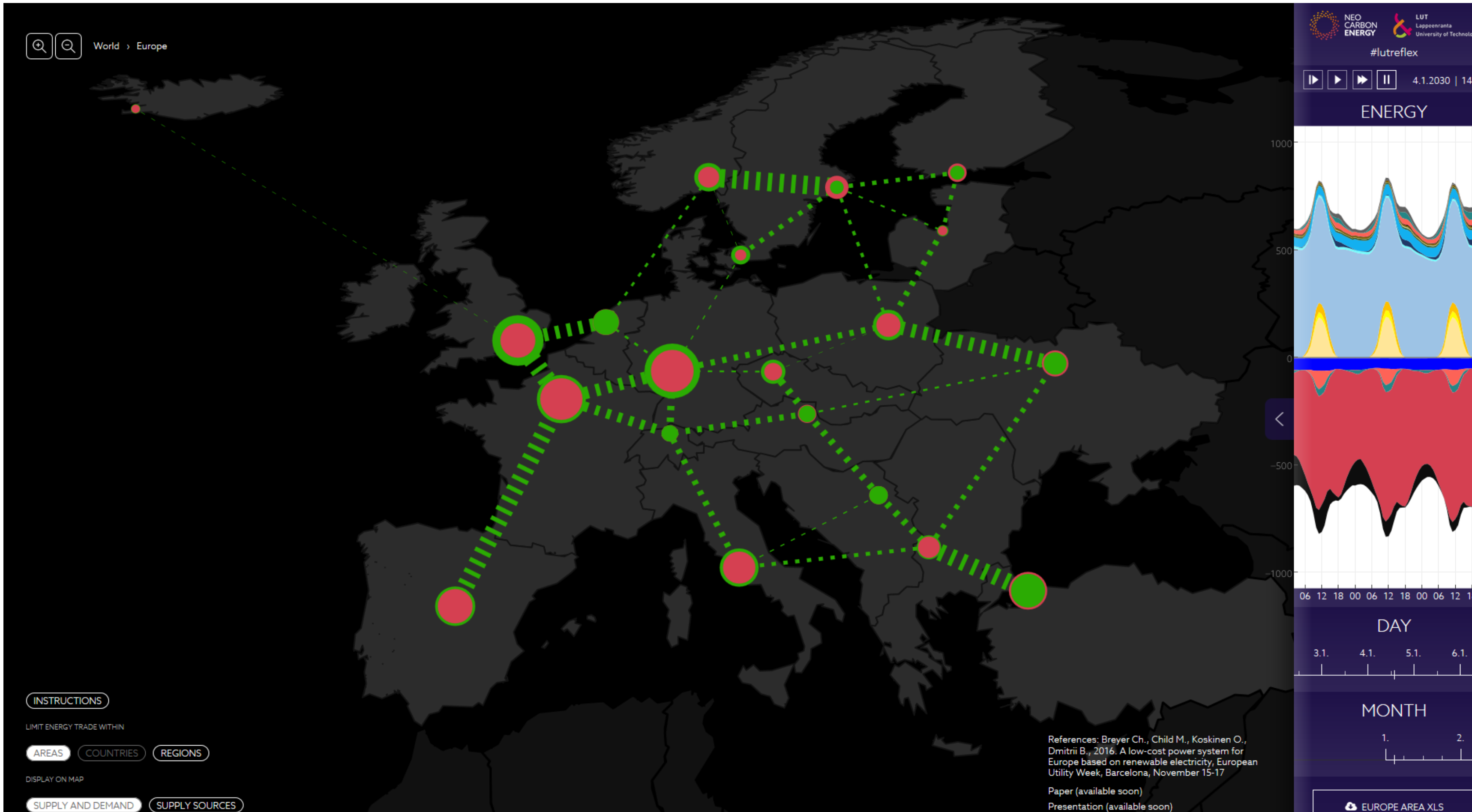
Key insights:

- India West exports 22 TWh of electricity to the grid (neighbouring regions)
- Energy mix is mainly based on PV, wind, hydro dams and biomass
- Monsoon month shows reduced solar resource but increased wind
- Batteries shift PV based electricity in the afternoon and night
- Batteries support grid exports and continuous PtG operation in night hours

source: [Gulagi A., et al., 2016. Solar Photovoltaics – A driving force towards a 100% renewable energy system for India and the SAARC region, 32nd EU PVSEC, Munich, June 20-24]

Results Visualisation

[Global Internet of Energy](http://neocarbonenergy.fi/internetofenergy/#): http://neocarbonenergy.fi/internetofenergy/#



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Demand for solar PV (2030, integrated)

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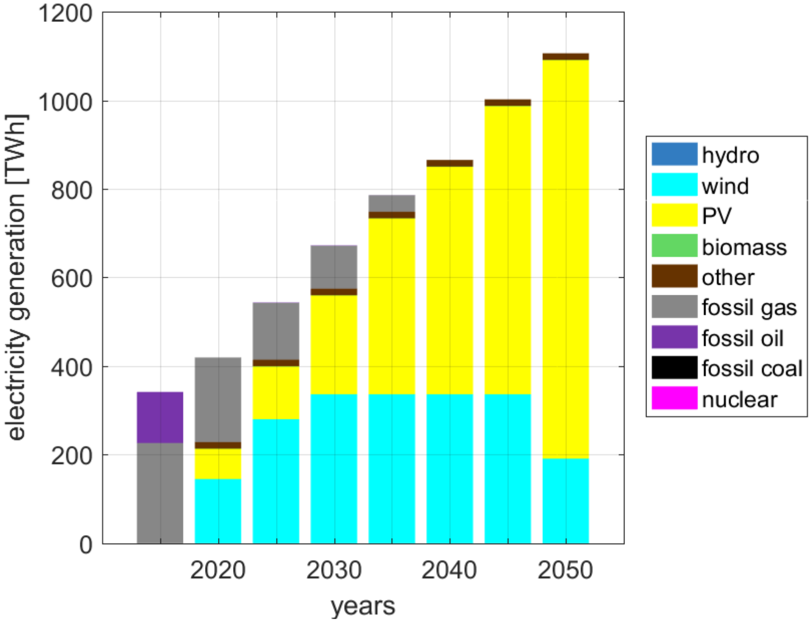
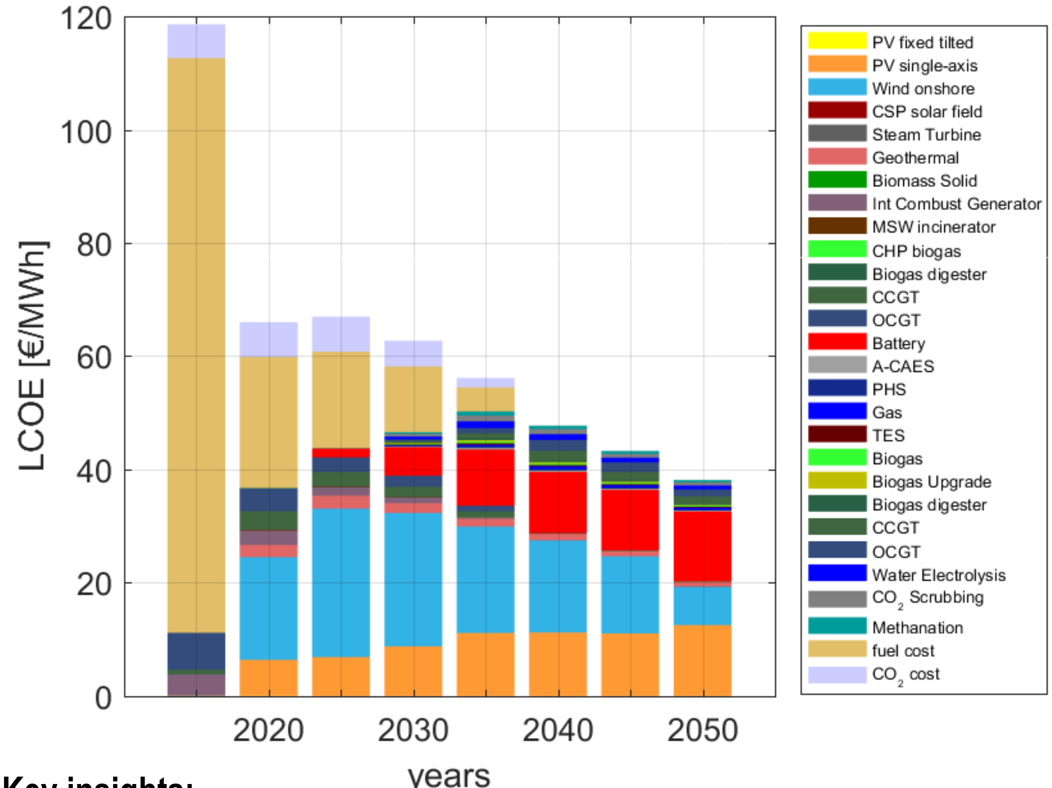
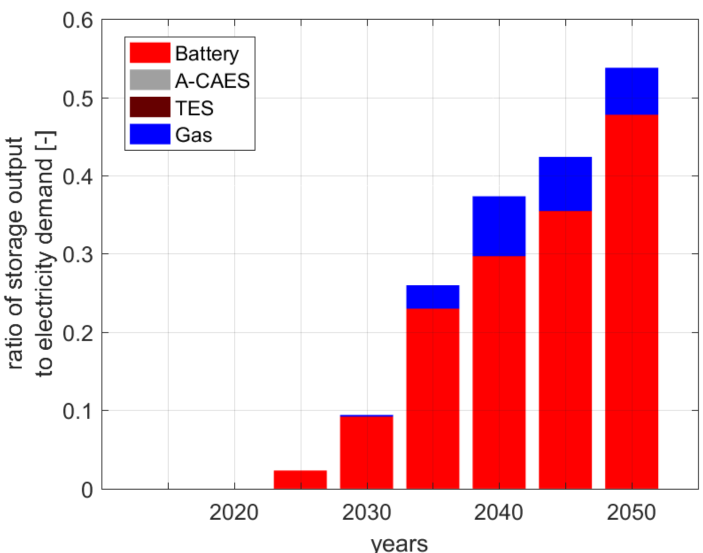
	Population 2030	Electricity demand 2030	Electricity demand 2030	PV prosumer	PV plants	PV total	PV electricity	PV share
integrated		electricity	integrated					
	[mil]	[TWh]	[TWh]	[GW_p]	[GW_p]	[GW_p]	[TWh]	[%]
Northeast Asia	1546	9878	13496	1509	2806	4315	6986	48 %
Southeast Asia	646	1630	2635	150	609	758	1425	51 %
India/ SAARC	1922	2597	3376	145	815	960	1880	50 %
Eurasia	244	1450	2550	92	171	263	388	15 %
Europe	675	4183	5127	608	353	991	1384	27 %
MENA	529	1813	7917	85	1668	1755	4098	49 %
Sub-Saharan Africa	1384	866	1223	61	241	302	636	48 %
North America	558	6059	10304	812	1038	1850	3452	32 %
South America	445	1813	2780	268	496	764	1419	48 %
World	7949	30289	49408	3730	8197	11958	21668	41 %
				31 %	69 %			

Energy Transition Modeling: Saudi Arabia





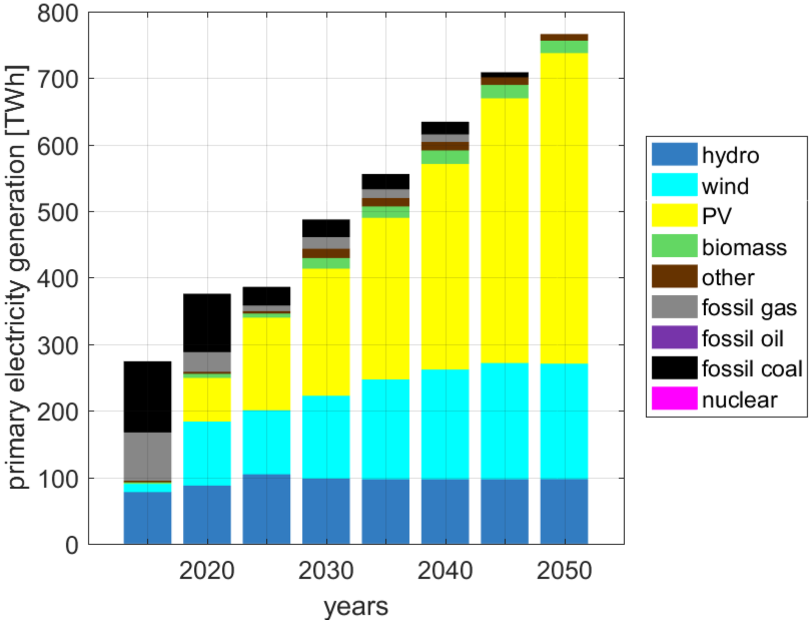


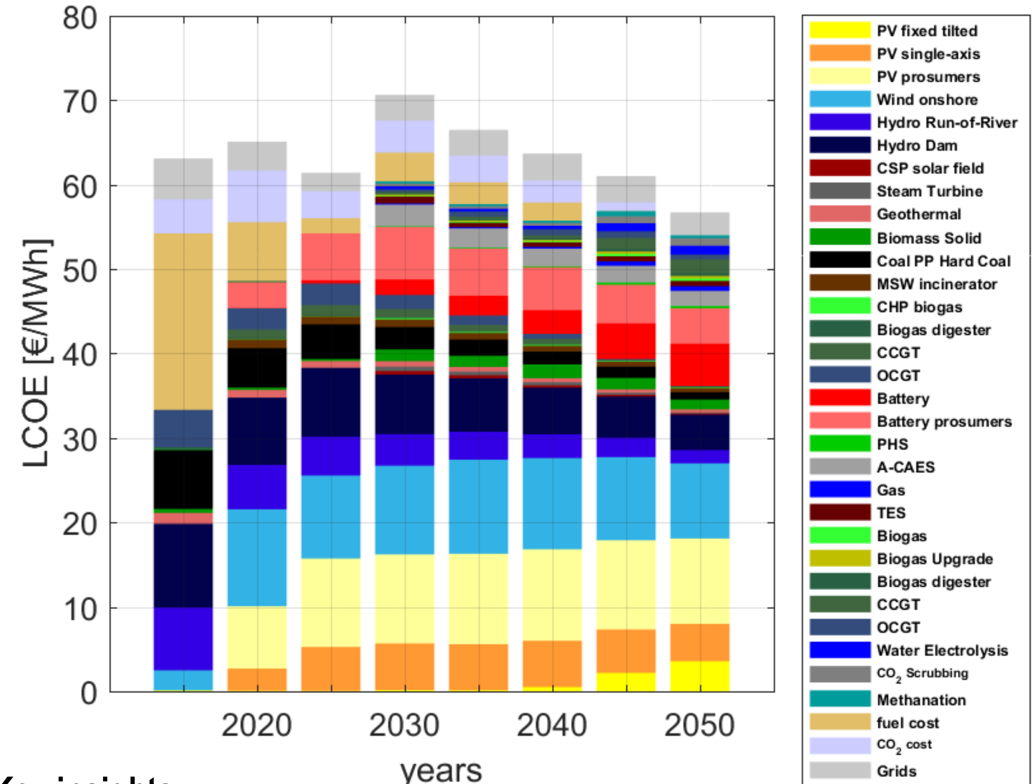
Key insights:

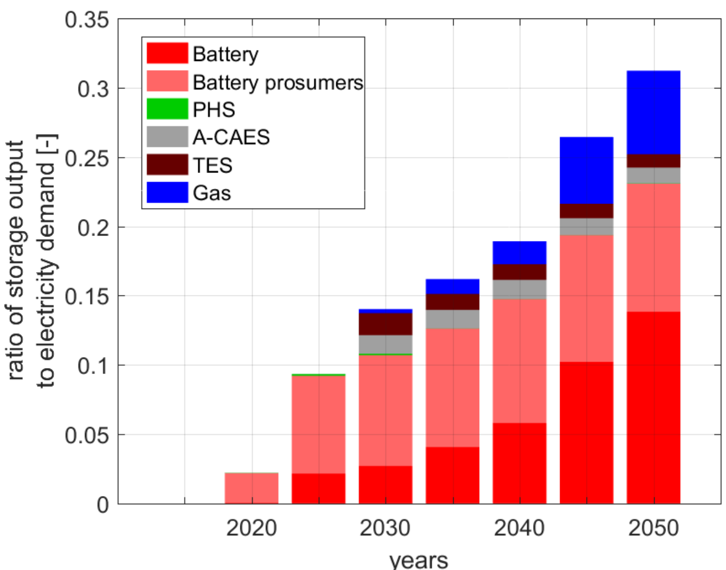
- energy system transition model for Saudi Arabia
- steady LCOE decline on energy system level driven by PV + battery
- beyond 2030 solar PV becomes more comeptitve than wind energy
- solar PV + battery finally runs the system more and more
- solar PV supply share in 2050 at about 81% (!!) as least cost

source: [Caldera U., et al., 2016. Integration of SWRO desalination in the power sector, based on PV and wind energy, for Saudi Arabia, 32nd EU PVSEC, Munich, June 20-24]

Energy Transition Modeling: Turkey





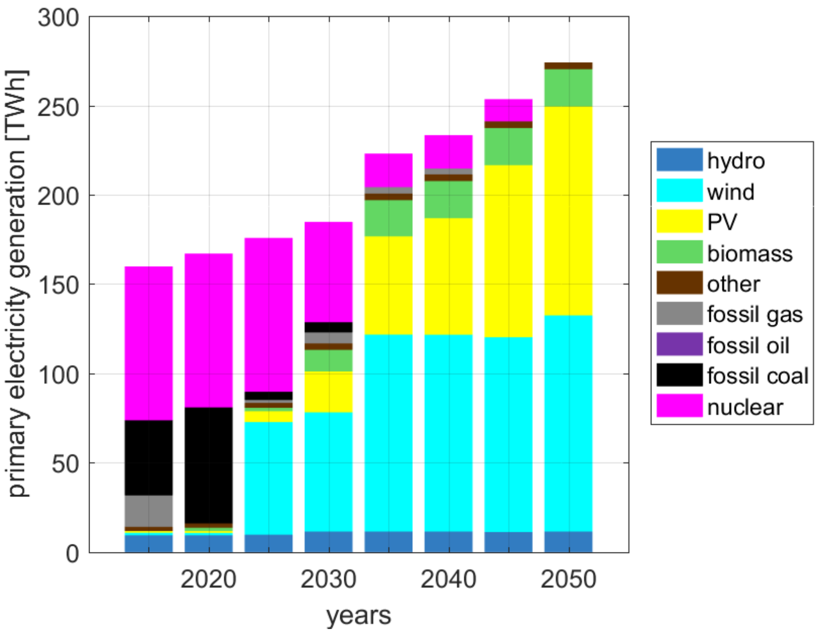


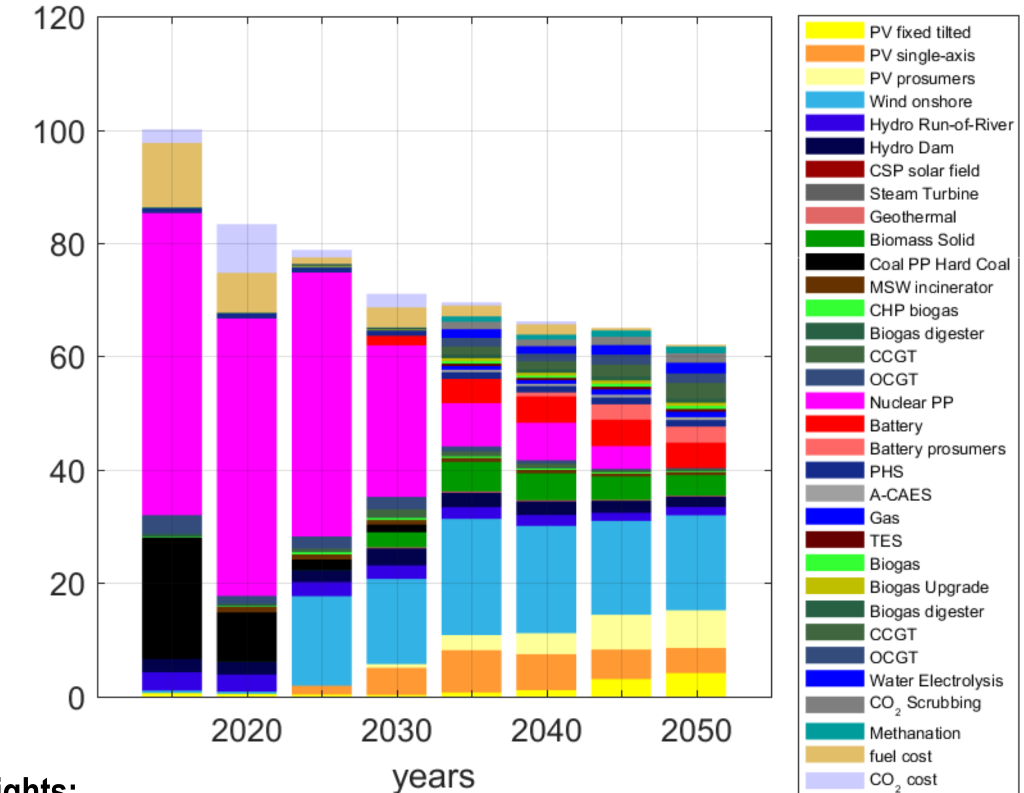
Key insights:

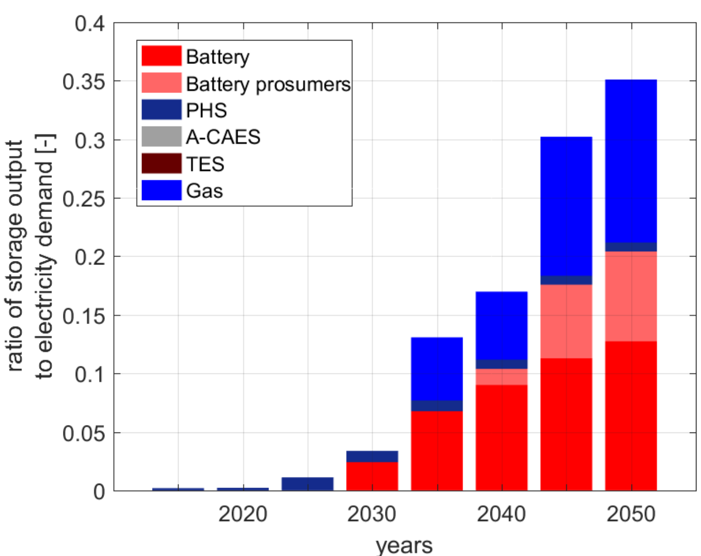
- energy system transition model for Turkey
- LCOE stays roughly stable and declines after 2040
- beyond 2030 solar PV becomes more comeptitve than wind energy
- solar PV + battery the most important system components
- solar PV supply share in 2050 at about 60% as least cost
- PV prosumers will play a very important role in Turkey

source: Kilickaplan A., Peker O., et al., 2016. The first electricity transition scenario for Turkey from now to 2050 for 100% renewables, SOLAR TR2016, Istanbul, December 7

Energy Transition Modeling: Ukraine







Key insights:

- energy system transition model for Ukraine
- steady LCOE decline on energy system level driven by wind, PV, battery, PtG
- transition pushed first by wind energy, then PV (2050 share around 40%)
- coal and nuclear phase-out doable and system cost decline
- PV prosumers play a larger role beyond 2030 (further pushed by batteries)
- … we currently check 90 countries globally in the same style

source: Child M., Bogdanov D., Breyer Ch., 2016. Transition towards a 100% Renewable Energy System by 2050 for Ukraine, SEF-2016, Kiev, Ukraine, October 11

Demand for solar PV

- 12.0 TWp demand for 100% RE and 2030 demand due to integrated scenario
- integrated scenario covers only about 45% of total primary energy demand (TPED)
- net zero constraint requires almost full electrification of all energy sectors
- almost all TPED can be electrified (except some industrial processes)
- 27.4 TWp demand for 100% RE and 2030 demand for full sector integration at about 41% solar PV contribution share

- 2030 TPED may be about 60% of TPED for 10 billion people on current European level
- 42 TWp demand by end of 21st century

- latest energy system transition modeling indicates a solar PV share increasing further for beyond 2030 cost assumptions, up to 80%, driven by low cost PV + battery

Further (preliminary) Insights

- Prosumer PV is a major trend all around the world (not at highly subsidised power)
- batteries are the most suited storage technology for solar PV
- major electricity generation technologies are solar PV and wind energy
- electricity based energy system is very efficient (e.g. electric vehicles, heat pumps)
- generation rather close to demand (storage competitive to long-distrance supply)
- storage demand typically overestimated due to lack of sector integrated view
- PV share expected to rise due to highly competitive relative cost trend of PV and batteries compared to other technologies (range from 40% up to 80%)
- fossil CCS and nuclear energy not competitive based on full cost
- leading reports are BNEF and Greenpeace
- net zero world does not mean a reduced standard of living but smart technologies
- the burning age ends, due to low efficiency and high societal costs

Thanks for your attention …
… and to the team!

NEO CARBON ENERGY

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The authors gratefully acknowledge the public financing of Tekes, the Finnish Funding Agency for Innovation, for the 'Neo-Carbon Energy' project under the number 40101/14.

all publications at: www.researchgate.net/profile/Christian_Breyer
new publications also announced via Twitter: @ChristianOnRE

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Scenarios assumptions

Financial assumptions (year 2030)

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Generation costs

Technology	Capex [€/kW]	Opex fix [€/(kW·a)]	Opex var [€/kWh]	Lifetime [a]
PV fixed-tilted	550	8	0	35
PV rooftop	813	12	0	35
PV single-axis	620	9	0	35
CSP	528	11	0	25
Wind onshore	1000	20	0	25
Geothermal	4860	87	0	30
Hydro Run-of-River *	2560	115.2	0.005	60
Hydro Dam *	1650	66	0.003	60
Water electrolysis	380	13	0.001	30
Methanation	234	5	0	30
CO_2 scrubbing	356	14	0.0013	30
CCGT	775	19	0.002	30
OCGT	475	14	0.011	30
Biomass CHP	2500	175	0.001	30
Waste incinerator	5240	235.8	0.007	20
Biogas CHP	370	14.8	0.001	20
Hot heat burner	100	2	0	30
Heating rod	20	0.4	0.001	30
Biogas digester	680	27.2	0	20
Biogas upgrade	250	20	0	20
Steam Turbine	600	12	0	30

Technology	Capex [€/(m³·a)]	Opex fix [€/(m³·a)]	Opex var [€/(m³)]	Lifetime [a]
Water Desalination	2.23	0.097	0	30

Technology	Energy/Power Ratio [h]
Battery	6
PHS	8
A-CAES	100
TES	8
Gas Storage	80*24

	Efficiency [%]
Battery	90
PHS	85
TES	90
A-CAES	70
Gas Storage	100
Water Electrolysis	84
CO_2 Scrubbing	78
Methanation	77
CCGT	58
OCGT	43
Geothermal	24
Biomass CHP	40
MCW Incinerator	34
Biogas CHP	40
Biogas upgrade	98
Hot heat burner	95
Heating rod	99
Steam Turbine	42
CSP collector	51

* hydro power plants older than 50 years are taken into account with refurbishment capex of 500 €/kW for 30 years

Scenarios assumptions

Financial assumptions (year 2030)

Storage and transmission costs

Technology	Capex [€/kWh]	Opex fix [€/(kWh·a)]	Opex var [€/kWh]	Lifetime [a]
Battery	150	10	0.0002	10/20
PHS	70	11	0.0002	50
A-CAES	31	0.4	0.0012	40
Gas storage	0.05	0.001	0	50

Technology	Capex [€/(m^3·h)]	Opex fix [€/(m^3·h·a)]	Opex var [€/(m^3·h)]	Lifetime [a]
Water storage	65	1	0	50

Technology	Capex [€/(m^3·h·km)]	Opex fix [€/(m^3·h·km·a)]	Energy consumption [kWh/(m^3·h·km)]	Lifetime [a]
Horizontal pumping	15	2.3	0.0004	30
Vertical pumping	23	2.4	0.0036	30

Technology	Capex [€/(kW·km)]	Opex fix [€/(kW·km·a)]	Opex var [€/kW]	Lifetime [a]
Transmission line	0.612	0.0075	0	50

Technology	Capex [€/kW]	Opex fix [€/(kW·a)]	Opex var [€/kW]	Lifetime [a]
Converter station	180	1.8	0	50

WACC = 7%

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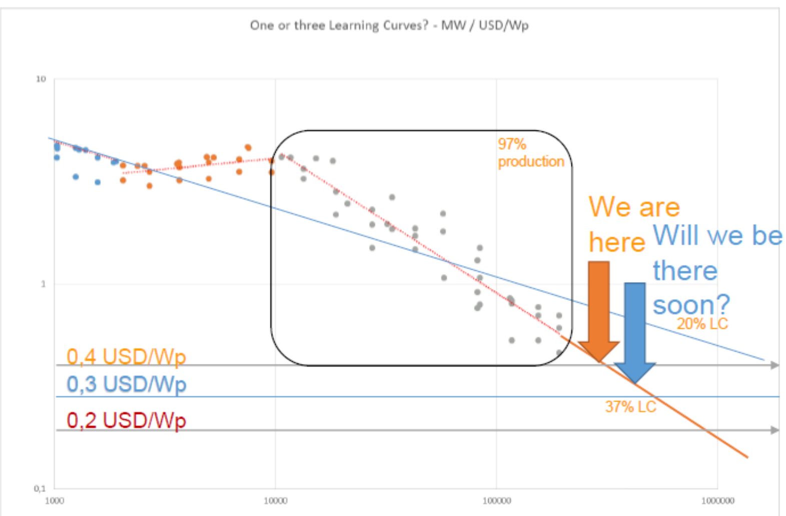
Scenarios assumptions

Financial assumptions (year 2030): Review on solar PV

Key insights:

- utility-scale PV in India in 2016 about 670 €/kWp
- market players expect about 600 €/kWp in 2017/2018
- we assume in our scenarios 550-620 €/kWp for 2030
- current PV module learning rates are now for some years substantially (about 2x) higher than in history (representing 97% of historic manufactured volume)
- leading global manufacturers expect a continuation for (at least) the mid-term
- we have to revise our utility-scale PV capex assumptions!



Source: Becquerel Institute 2016

Source: Masson G., 2016. PV Trends & Market Overview, Director Bequerel Institute, OA IEA-PVPS Task 1, former policy & market expert EPIA

CENTRAL ELECTRICITY REGULATORY COMMISSION
NEW DELHI

Petition No. 17/SM/2015

Coram: Shri Gireesh B. Pradhan, Chairperson
Shri A. K. Singhal, Member
Shri A. S. Bakshi, Member
Shri M.K.Iyer, Member

Date of Order: 23rd March 2016

IN THE MATTER OF

Determination of Benchmark Capital Cost Norm for Solar PV power projects and Solar Thermal power projects applicable during FY 2016-17

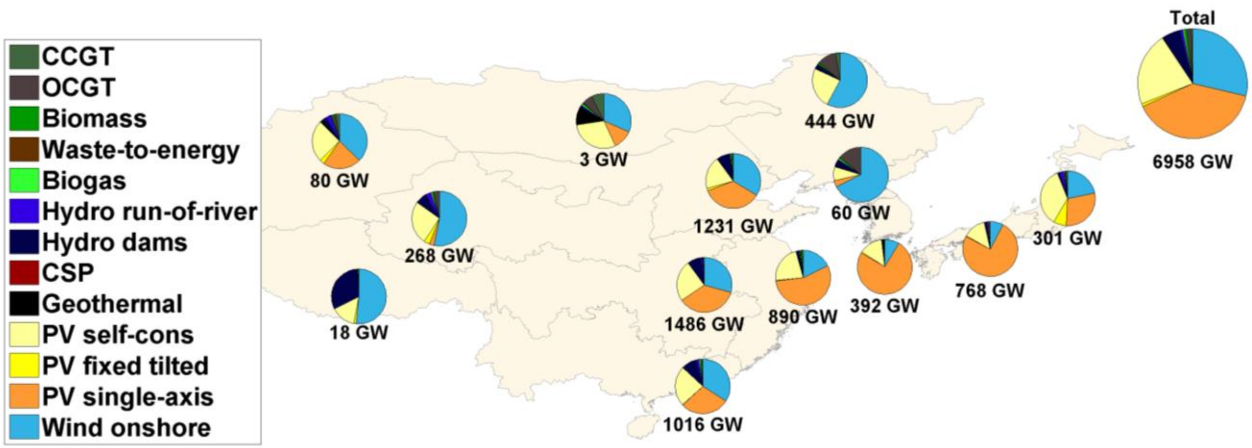
11. Overall Capital Cost

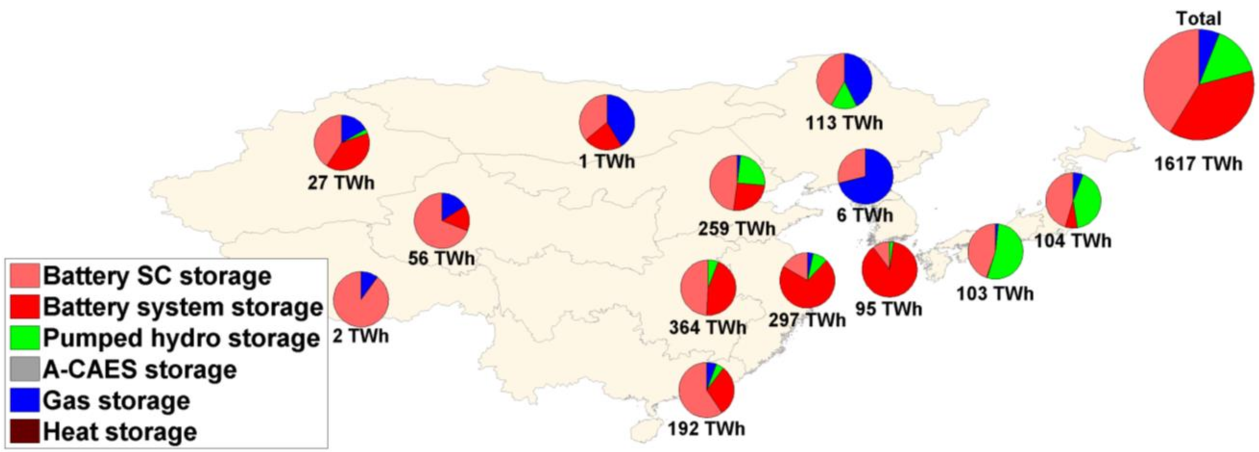
Commission's Proposal

S.No.	Particulars	Capital Cost norm proposed for FY 2016-17 (Rs. lakhs/MW), for Solar PV projects	% of Total Cost
1	PV Modules	310.19	61.9%
2	Land Cost	25	5%
3	Civil and General Works	35	7%
4	Mounting Structures	35	7%
5	Power Conditioning Unit	30	6%
6	Evacuation Cost up to Inter-connection Point (Cables and Transformers)	40	8%
7	Preliminary and Pre-Operative Expenses including IDC and Contingency	26.13	5.2%
	Total Capital Cost	**501.32**	**100%**

505.3 INR/kWp = 668 EUR/kWp (exchange rate 75 INR/€ as good ave of present and past)

Results: China/ Northeast Asia





Key insights:

- population of 1546 mil
- electricity demand of 9878 / 13496 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 3351 GW 41% (region), 2828 GW 40% (area), 4315 GW 48% (integrated)
- storage of 20% / 16% / 12% of final electricity demand, thereof battery share of 67% / 68% / 79% for region / area / integrated
- trading among sub-regios of 11% / 10% for area / integrated

* these results show updated numbers comparred to inital publication based on financial and technical assumptions for all major regions

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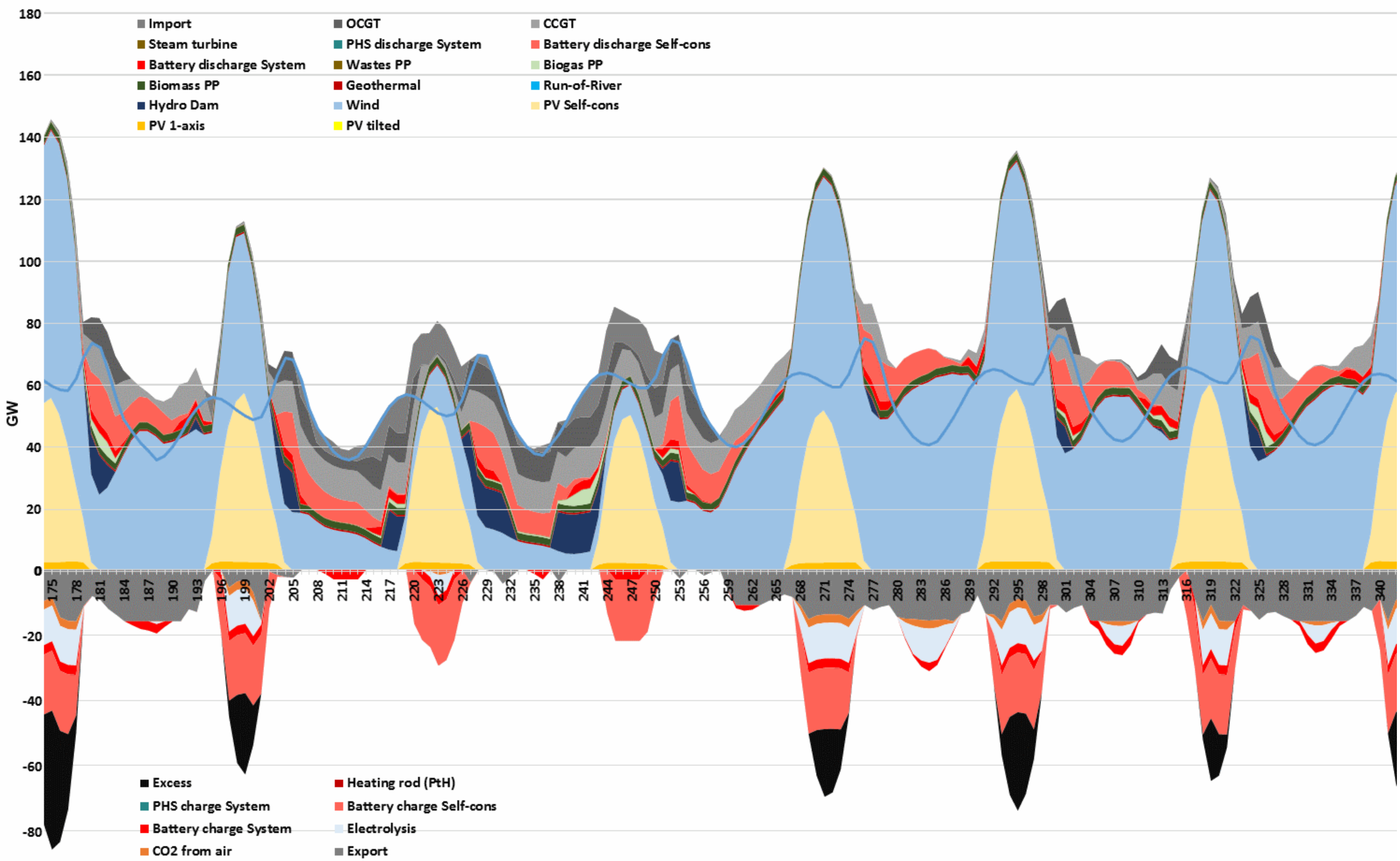
source: Bogdanov D. and Breyer Ch., 2016. North-East Asian Super Grid for 100% Renewable Energy supply: Optimal mix of energy technologies, Energy Conv. Manag, 112, 176-190

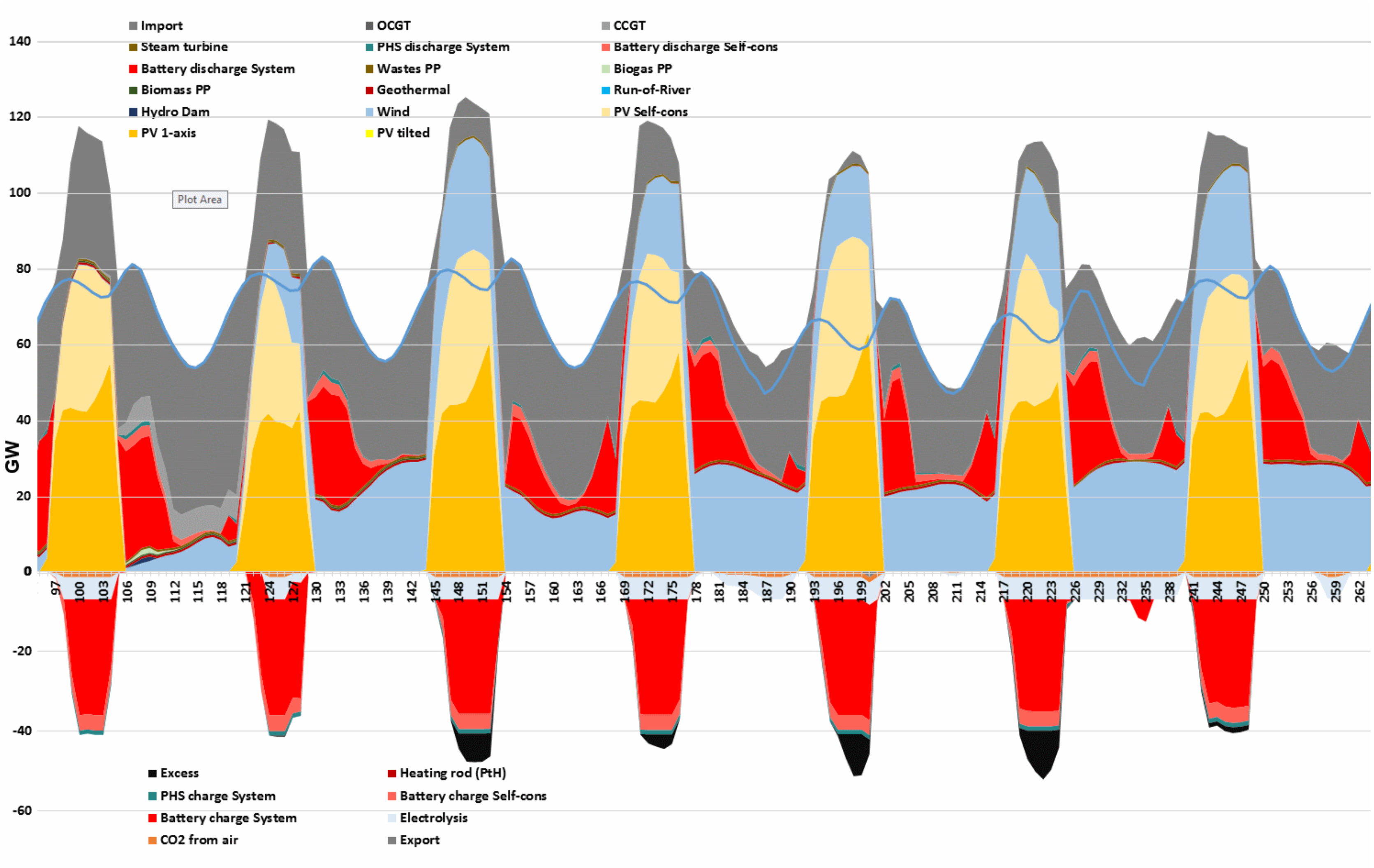
Results

Balancing region – Northwest China



Results

Net importer region – South Korea



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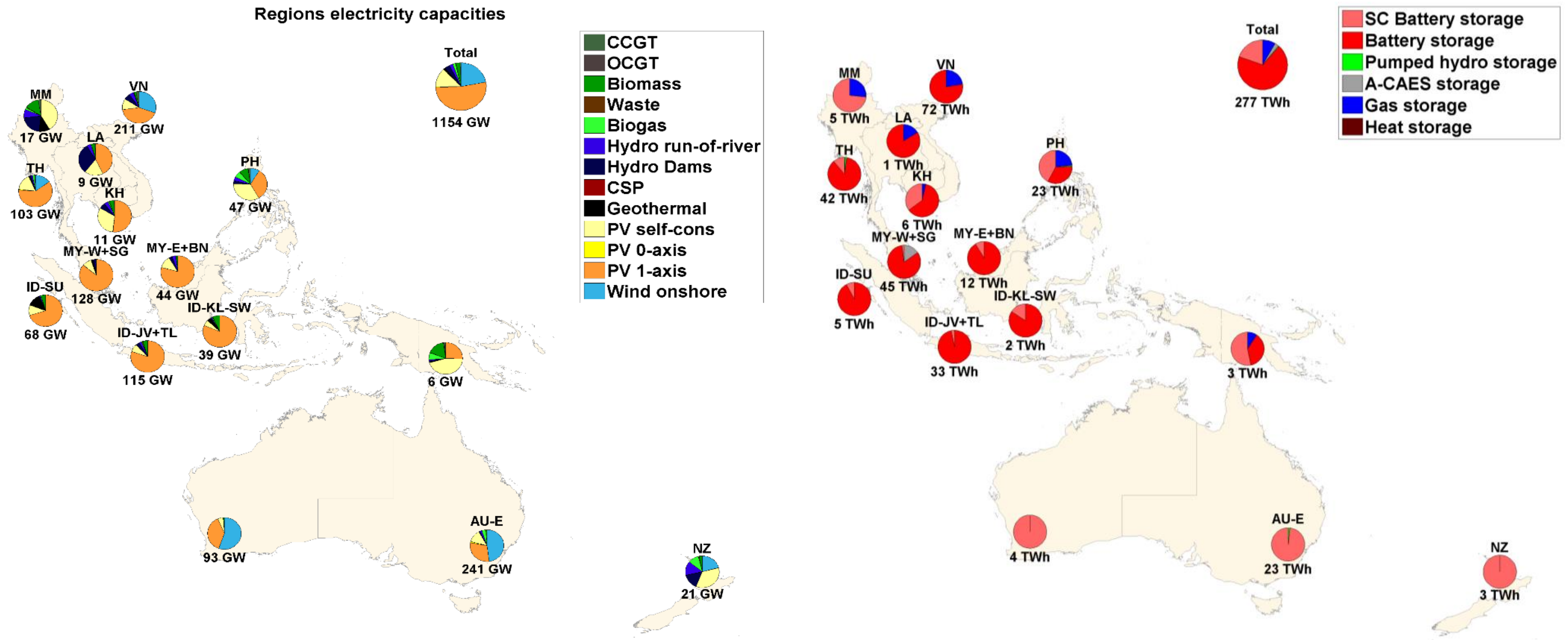
Results: Southeast Asia



Key insights:

- population of 646 mil, electricity demand of 1630 / 2635 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 502 GW 50% (region), 448 GW 46% (area), 758 GW 51% (integrated)
- storage of 20% / 17% / 11% of final electricity demand, thereof battery share of 75% / 80% / 88% for region / area / integrated
- trading among sub-regios of 6% / 3% for area / integrated

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source: Breyer Ch., Gulagi A., Bogdanov D., 2015. South-East Asia and the Pacific Rim Super Grid for 100% RE power supply, IEA-PVPS Task 1 Meeting – GÜNDER Workshop, Istanbul, October 27

Results

Net importer region – Malaysia West + Singapore

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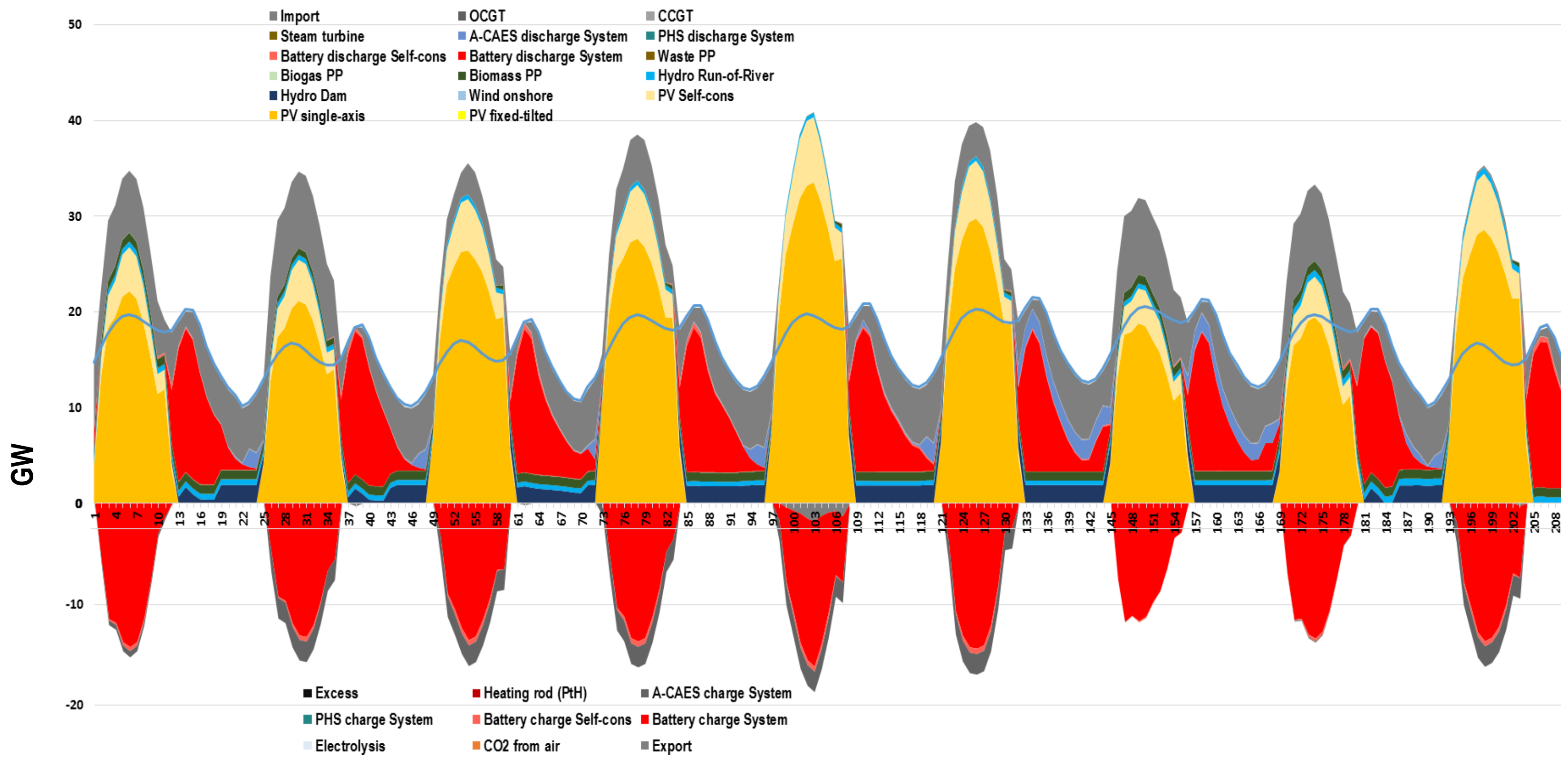
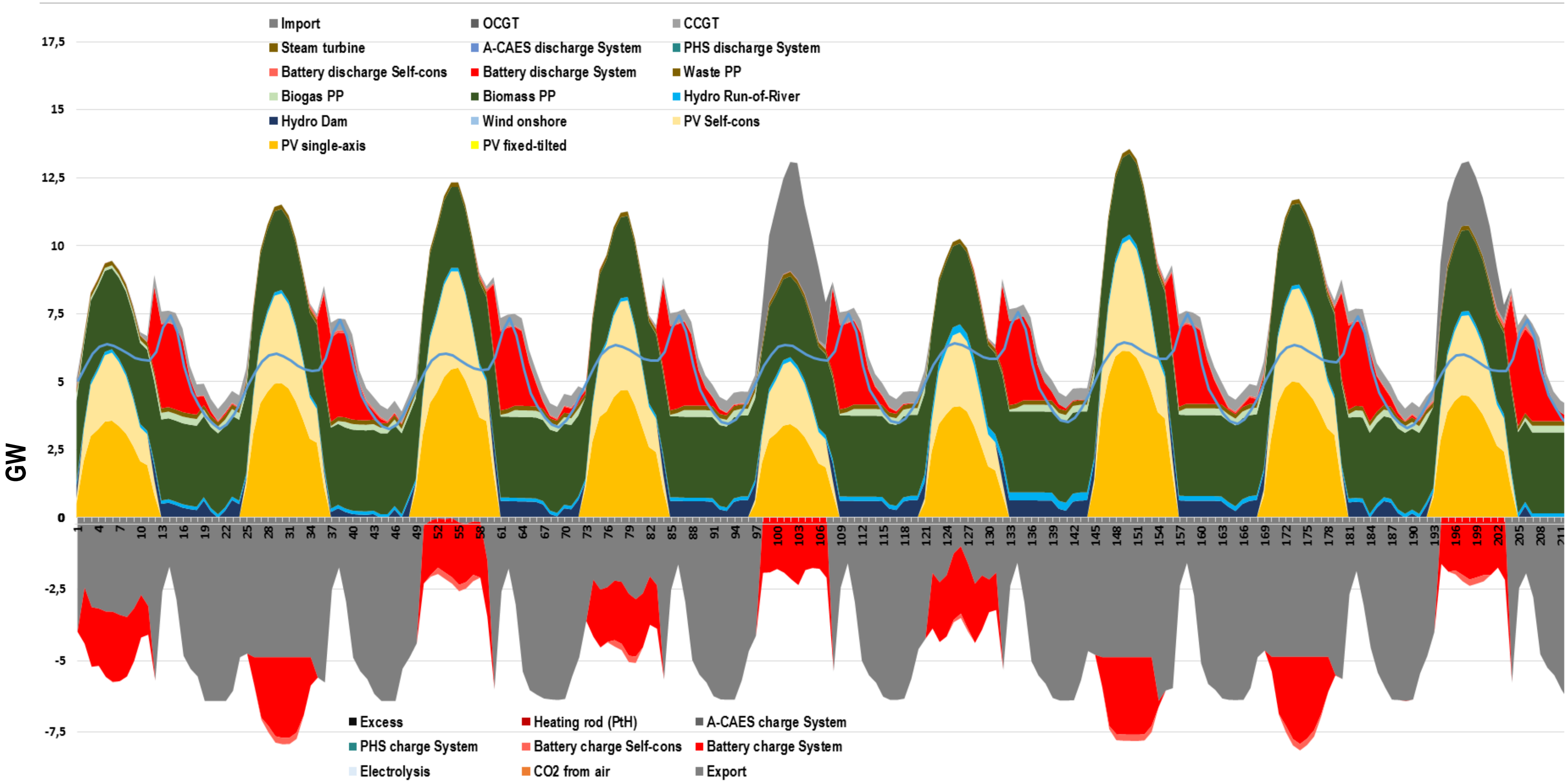


Key insights:

- Malaysia West + Singapore imports 31 TWh of electricity from the grid (neighbouring regions)
- own generation is based on PV (prosumer, single-axis)
- batteries and A-CAES charged during daytime and discharged in afternoon (only batteries) and evening (both)

Results

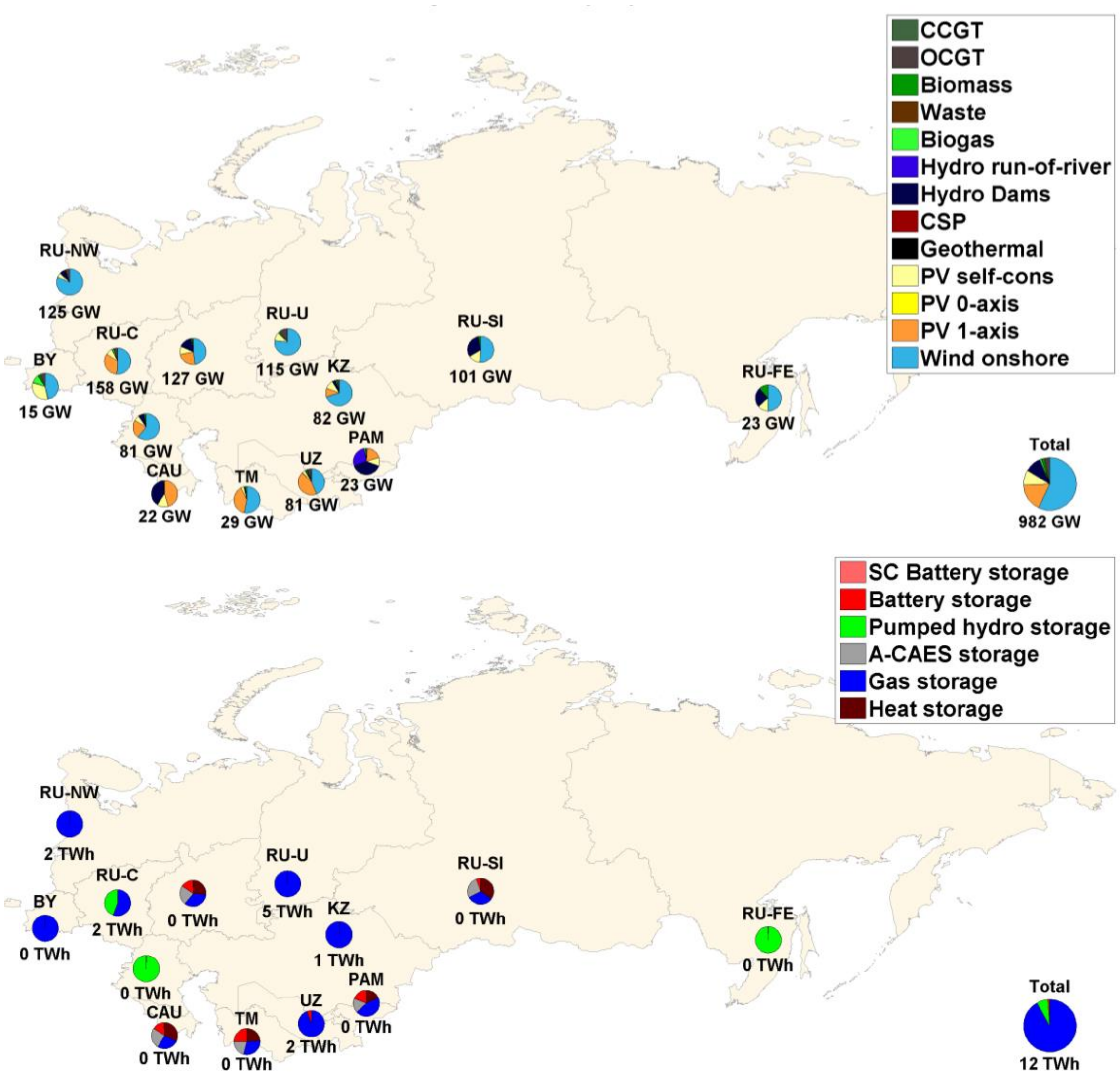
Net exporter region – Sumatra



Key insights:

- Sumatra exports 29 TWh of electricity to the grid (neighbouring regions)
- Energy mix is mainly based on PV (prosumers), hydro dams and biomass
- Batteries shift PV-based electricity in the afternoon and night
- Hydro dams and biomass is used flexibly in hours of no PV

Results: Russia/ Eurasia



Key insights:

- population of 244 mil
- electricity demand of 1450 / 2550 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 207 GW 16% (region), 113 GW 9% (area), 263 GW 15% (integrated)
- storage of 4% / 6% / 5% of final electricity demand, thereof battery share of 9% / 4% / 1% for region / area / integrated
- trading among sub-regios of 20% / 13% for area / integrated

source: [Bogdanov D. and Breyer Ch., 2015. Eurasian Super Grid for 100% Renewable Energy power supply: Generation and storage technologies in the cost optimal Mix]

Results

Net exporter region – North-West Russia

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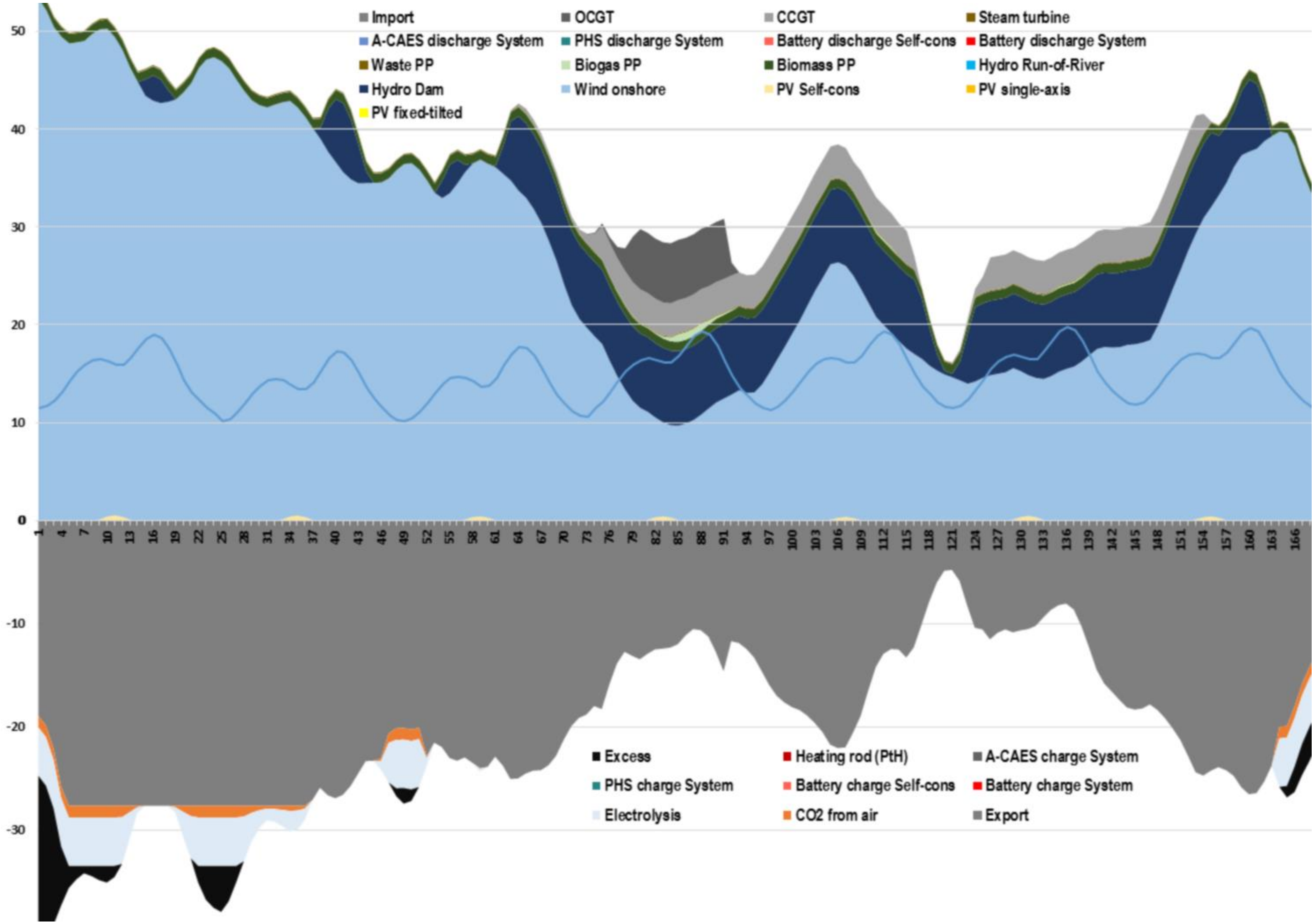
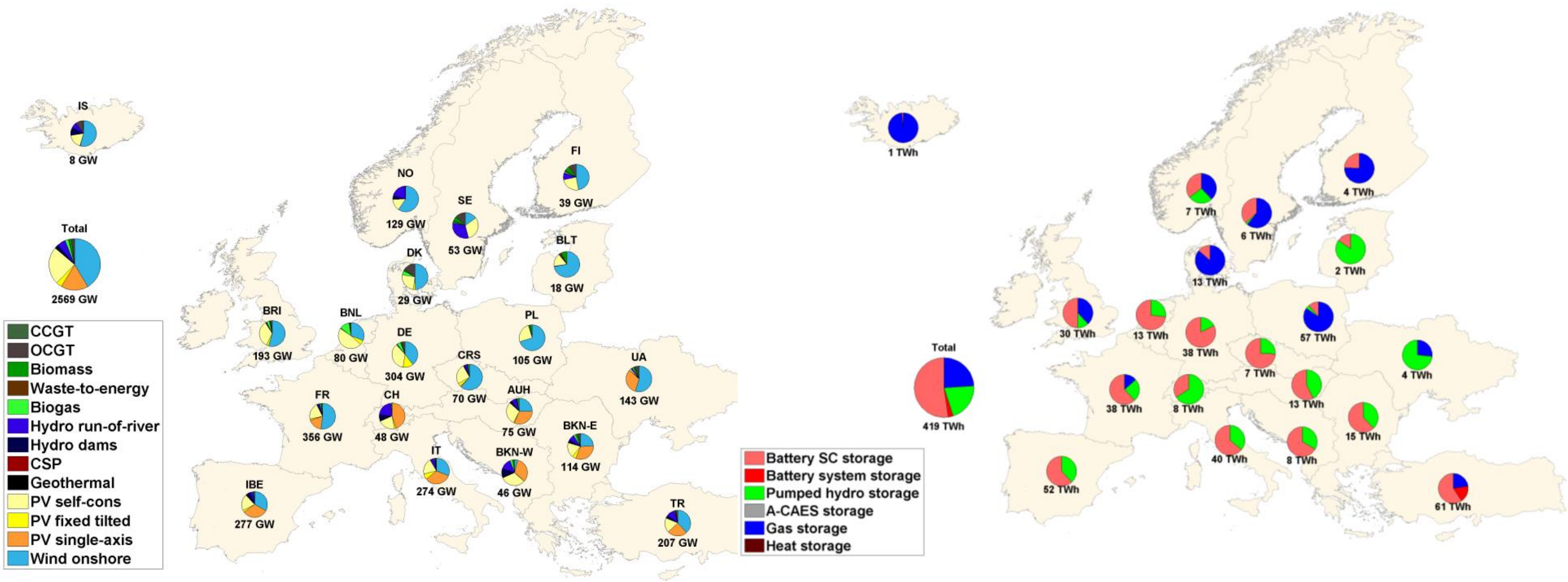


source: [Bogdanov D. and Breyer Ch., 2015. Eurasian Super Grid for 100% Renewable Energy power supply: Generation and storage technologies in the cost optimal Mix]

Results: Europe



Key insights:

- population of 675 mil, electricity demand of 4183 / 5127 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 1382 GW 30% (region), 781 GW 23% (area), 991 GW 27% (integrated)
- storage of 17% / 11% / 8% of final electricity demand, thereof battery share of 33% / 45% / 55% for region / area / integrated
- trading among sub-regios of 14% / 15% for area / integrated

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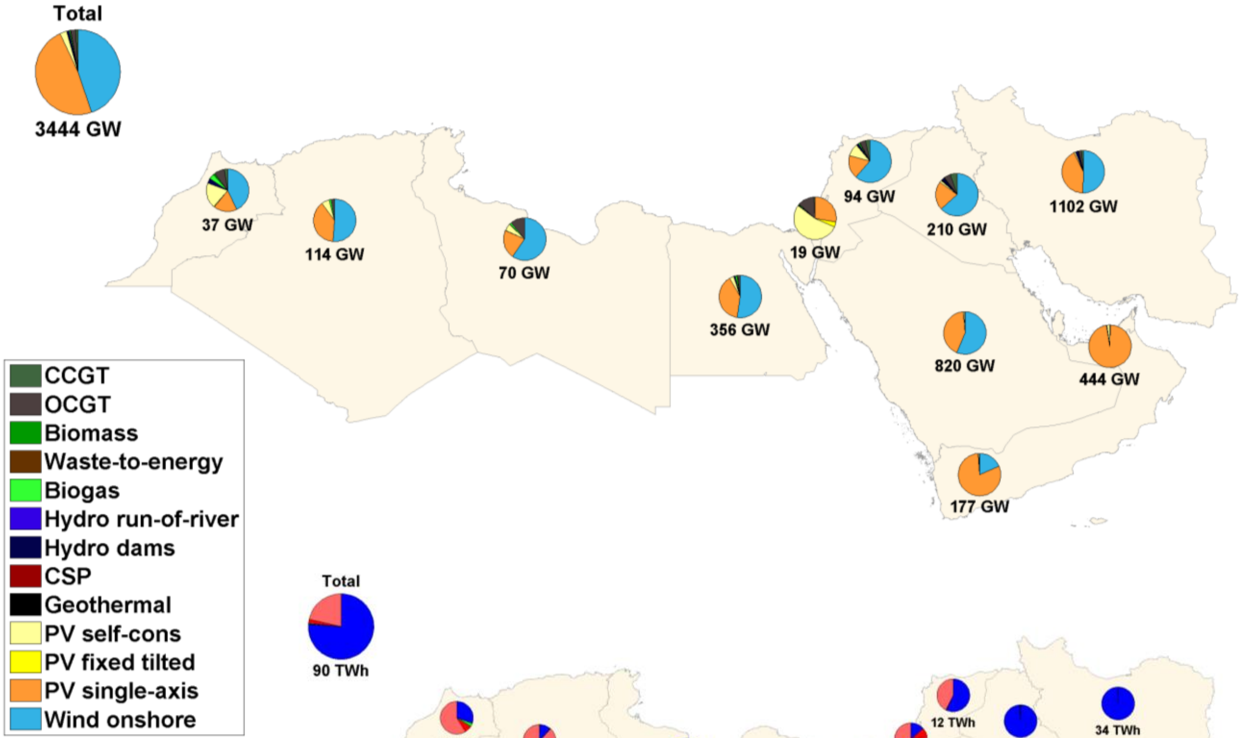
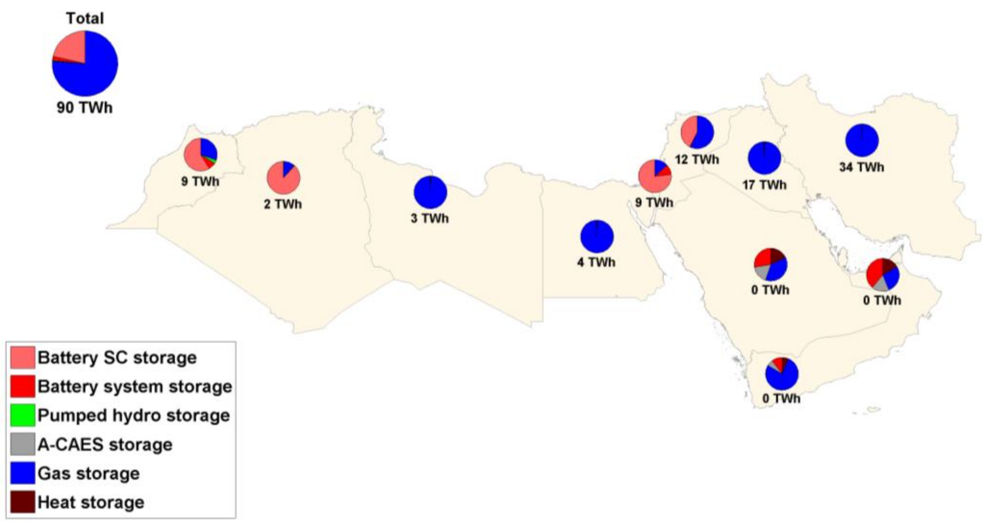
Results: Middle East North Africa (MENA)





Key insights:

- population of 529 mil
- electricity demand of 1813 / 7917 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 480 GW 50% (region), 358 GW 39% (area), 1755 GW 49% (integrated)
- storage of 18% / 11% / 11% of final electricity demand, thereof battery share of 53% / 63% / 23% for region / area / integrated
- trading among sub-regios of 12% / 10% for area / integrated

source: Aghahosseini A., et al., 2016. The MENA Super Grid towards 100% Renewable Energy Power Supply by 2030, 11th IEC, Tehran, May 30-31

Results: Sub-Saharan Africa

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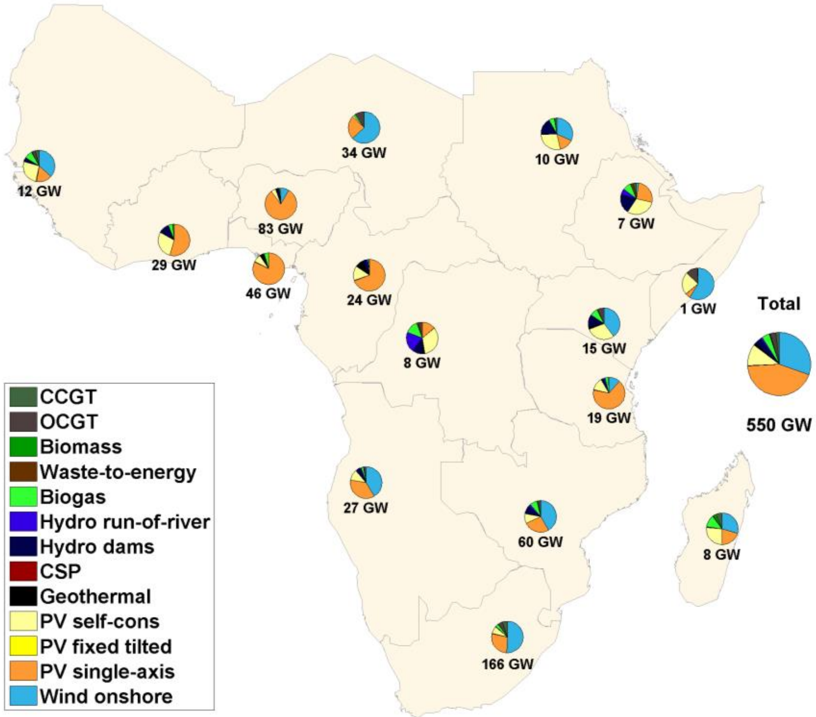

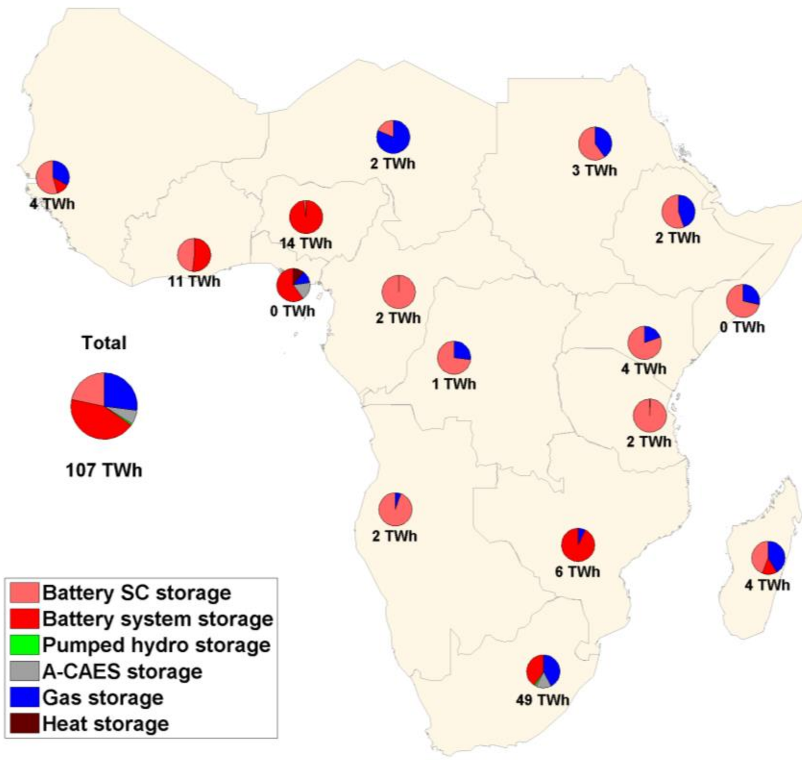

Key insights:

- population of 1383 mil, electricity demand of 866 / 1223 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 197 GW 42% (region), 174 GW 38% (area), 302 GW 48% (integrated)
- storage of 15% / 13% / 9% of final electricity demand, thereof battery share of 64% / 68% / 65% for region / area / integrated
- trading among sub-regios of 9% / 10% for area / integrated

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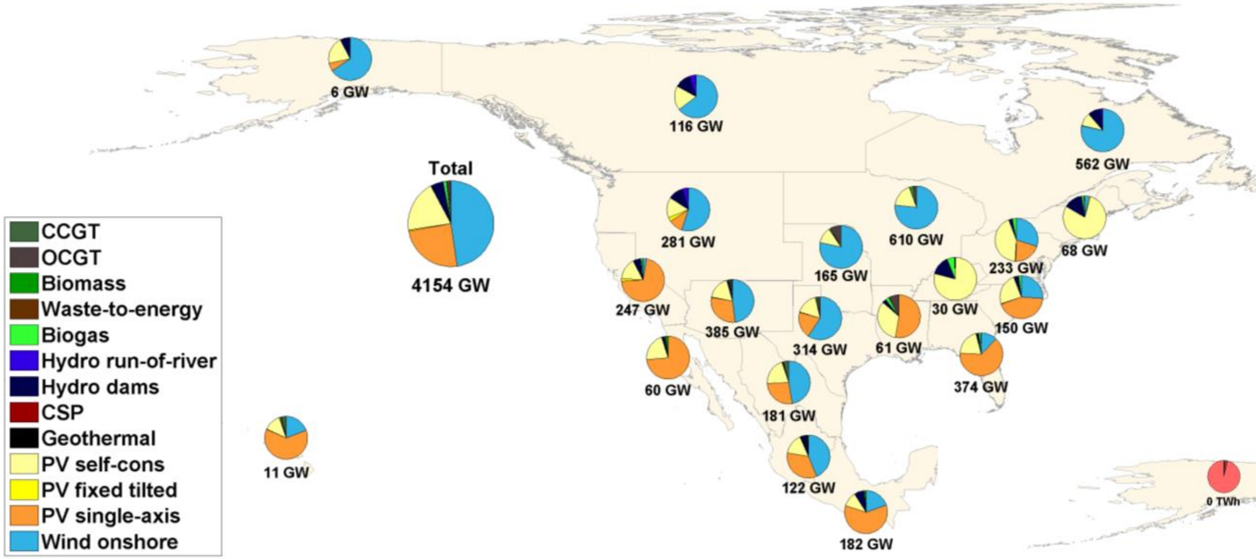
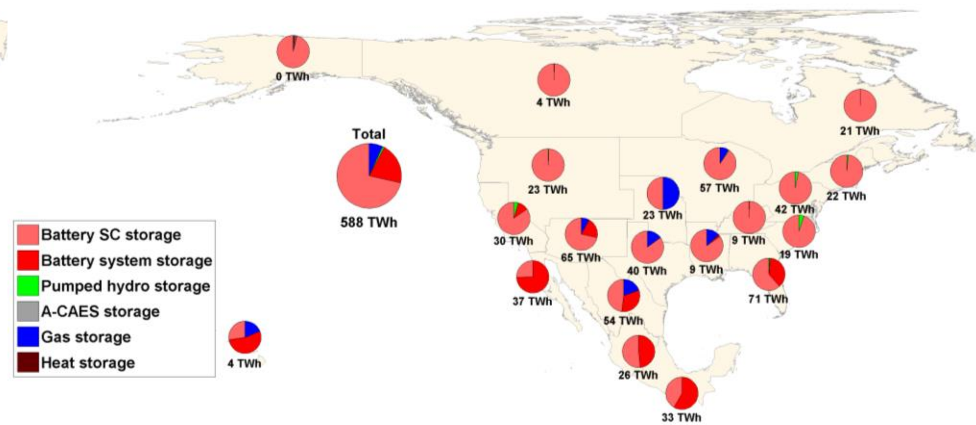
source: Barasa M., et al., 2016. A Cost Optimal Resolution for Sub-Saharan Africa powered by 100 Percent of Renewables by the Year 2030, 32nd EU PVSEC, Munich, June 20-24, (6AV.4.9, Mon 13:30)

Results: North America

source: Aghahosseini A., et al., 2016. 100% Renewable Energy in North America and the Role of Solar Photovoltaics, 32nd EU PVSEC, Munich, June 20-24, (7DV.4.8, Mon 13:30)





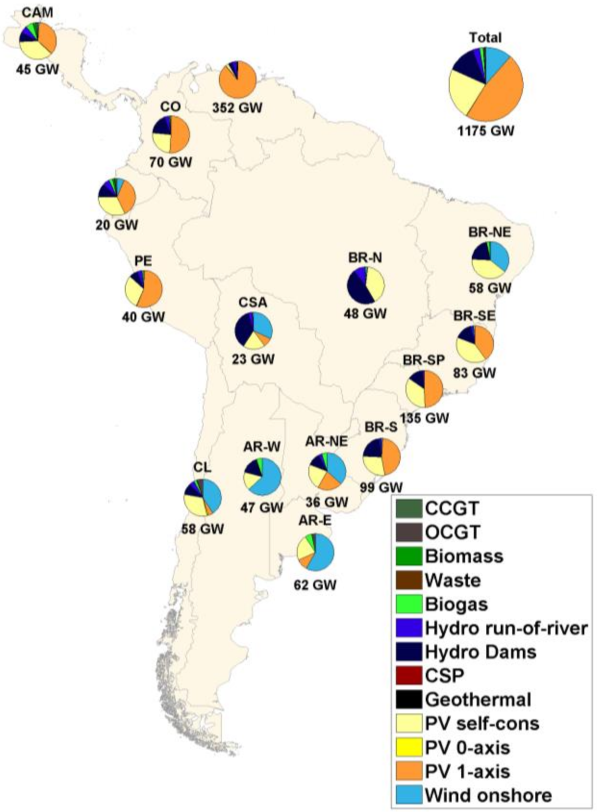
Key insights:

- population of 558 mil, electricity demand of 6059 / 10304 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 1895 GW 46% (region), 1286 GW 33% (area), 1850 GW 32% (integrated)
- storage of 21% / 13% / 6% of final electricity demand, thereof battery share of 63% / 72% / 96% for region / area / integrated
- trading among sub-regios of 23% / 24% for area / integrated

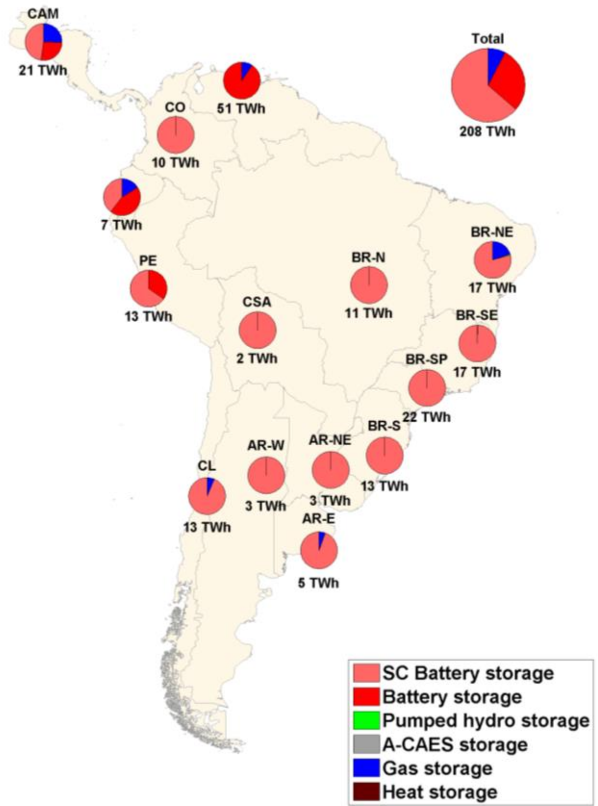
NEO CARBON

source: Aghahosseini A., et al., 2016. 100% Renewable Energy in North America and the Role of Solar Photovoltaics, 32nd EU PVSEC, Munich, June 20-24 (7DV.4.8 Thu 17:00)

Results: Brazil/ South America



source:
[Barbosa L., et al. 2015. Complementarity of hydro, wind and solar power as a base for a 100% RE energy supply for South and Central America]

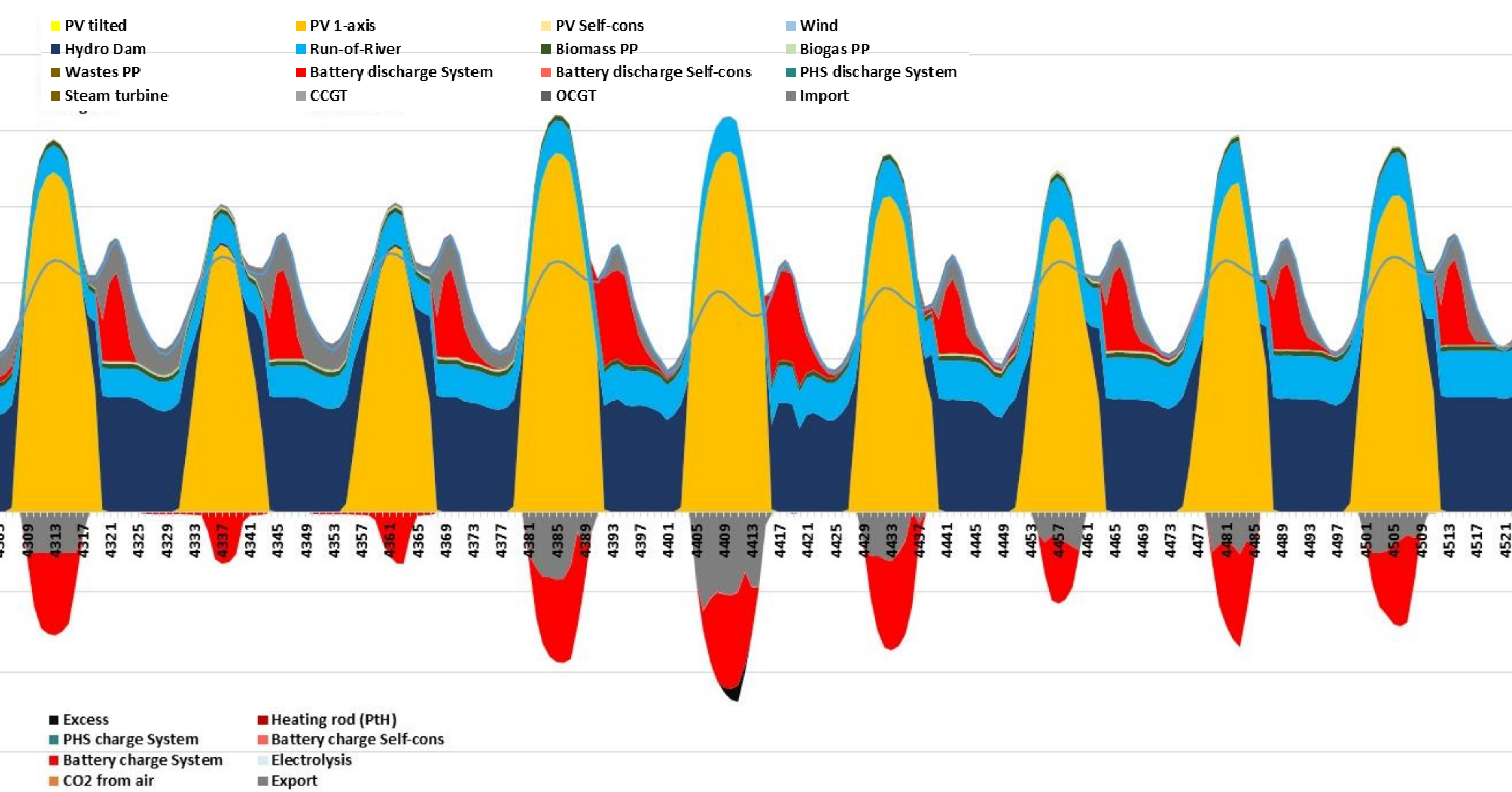


Key insights:

- population of 445 mil, electricity demand of 1813 / 2780 TWh_{el} for region&area / integrated
- solar PV abs in GW and rel in TWh of 446 GW 36% (region), 365 GW 33% (area), 764 GW 48% (integrated)
- storage of 13% / 8% / 7% of final electricity demand, thereof battery share of 90% / 99% / 91% for region / area / integrated
- trading among sub-regios of 11% / 8% for area / integrated

Results

Net importer region - Venezuela



source: [Barbosa L., et al. 2015. Complementarity of hydro, wind and solar power as a base for a 100% RE energy supply for South and Central America]